Study on Recycling of Waste Asphalt Blocks Containing Roadbed Materials

DOCTORAL THESIS

STUDY ON RECYCLING OF WASTE ASPHALT BLOCKS CONTAINING ROADBED MATERIALS

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ABSTRACT

Waste asphalt blocks from construction sites are usually processed in the recycling plants to be used as recycled asphalt aggregates. These blocks are usually fed into the grizzly to break them into small pieces and to remove the soil attached on their surfaces. At present, the soil content of grizzly-under-materials (a recycled aggregate obtained from waste asphalt blocks) does not satisfy the required standard value (Japan Road Association, 1992), that should be less than 5%.

Therefore, it was necessary to reduce the amount of soils in the grizzly-under-materials, to be used as expensive recycled aggregates. In 2009, at Takahashi Laboratory started the development of screenless separation equipment to remove the soils from grizzly-under-materials. This equipment was able to reduce the amount of soils in the grizzly-under-materials, but its efficiency was not high enough to match with the mentioned standard value.

In this study, the previous mentioned equipment was modified by adding a vibration device in order to reduce the pipe inclination angle with the goal to increase the grizzly-under-materials processing time in the equipment. It was found through the experiments that the vibration device worked well and the equipment efficiency to reduce the amount of soils increased compared with the previous equipment.

It was also found that the performance of the newly proposed screenless separation equipment increased with increasing the water content in the grizzly-under-materials from 3% to 5%. This behaviour of equipment performance was opposite from previous equipment. From this situation, it was necessary to carry out an experimental study on reduction of soil content in grizzly-under-materials setting the same conditions for experiment and processing the same sample, changing only the water content in the material to process. From those experiments, it was found that temperature can has a double effect on equipment performance and the success of soil reduction content activity will depend on the characteristics of the materials to process.

Besides, it was obtained a numerical model in an attempt to predict the behaviour of rate of suction of the equipment. In this process, it was considered as independent variables the specific characteristics of grizzly-under-materials and soil, furthermore the experimental conditions to be used for carrying out the experiments. It was found that clay and silt percent

in the soil have high and low effect on equipment performance respectively and the obtained numerical model can be used as a tool for decision-making at construction site.

It was also discovered that the success of soil reduction content activity depend on four different kind of factors: factors related with the equipment design, factors related with the characteristics of the GUM, factors related with the characteristics of soil contained in GUM and factors related with the weather conditions.

CHAPTER 1 INTRODUCTION

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1.1 Background

Every year many roads are damaged by heavy traffic and weather. These are the two main factors that cause the emergence of cracks on the road surface. Heavy traffic causes the surface cracking due to fatigue of the material by a great number of shear loadings of the pavement surface by the tyre, ageing of bituminous materials plays an important role here, too [1]; and weather causes the thermal cracking due to tensile stresses caused by temperature changes [1]. Figure 1 and figure 2 [2] show a photograph of surface cracking and thermal cracking respectively.

Fig. 1 Surface cracking

Fig. 2 Thermal cracking

Usually governments of many countries dedicate large amount of money to support and guarantee reparation actions over roads depending on the characteristics of damage. There are five main types of asphalt pavement recycling: full depth reclamation, hot in-place recycling, cold in-place recycling, cold planning and hot recycling [3].

Deteriorating roads are a constant problem for cities and countries. That's why engineers and public works officials are turning to a process called full-depth reclamation (FDR) with cement. It is an in-situ process that grinds up the existing asphalt pavement and aggregate base course and mixes both together and replaces it on the subgrade soil. With FDR, all of the pavement section and in some cases a predetermined amount of underlying material, are mixed with asphalt emulsion to produce a stabilized base course. Base problems can be corrected with this construction [3].

Hot in-place recycling, performed on-site, and the pavement typically is processed to a depth of 3/4 to 1-1/2 inch. The asphalt pavement is heated, softened and scarified to the depth specified. An asphalt emulsion or other recycling agent is added, and with one of the processed, new HMA is incorporated as required. The three hot in-place recycling methods are heater-scarification, repaving and remixing [3].

Cold in-place recycling (CIR) is defined as a rehabilitation technique in which the pavement materials are reused in the same place. For CIR, the existing asphalt pavement typically is processed to the depth of 2 - 4 inches. In this process the materials are mixed in-place without the application of heat. The pavement is pulverized and the reclaimed materials is mixed with an asphalt emulsion or emulsified recycling agent, spread and compacted to produce a base course. Cold recycling bases required a new asphalt surface. The lower traffic pavement may use an asphalt emulsion surface treatment while a higher traffic pavement uses a modified emulsion surface treatment or an HMA surface [3].

In cold planning, the asphalt pavement is removed to specific depth and the surface is restored to a desired grade and cross slope with free of humps, rut and other surface imperfections. The depth of pavement removed is usually between one and two inches. This pavement removal or milling is completed with a self-propelled rotary drum cold planning machine. The reclaimed asphalt pavement (RAP) is transferred to a truck for removal and stockpiled for hot and cold recycling [3].

In hot recycling, RAP is combined with new aggregate and asphalt cement and/or recycling agent to produce HMA. Although, batch type hot mix plants are used, drum plants typically are used to produce the recycled mix. Most of the RAP in this process is taken from cold planning. The mix placement and compacting equipment and procedure are those typical of HMA construction [3].

Once removed and processed, the pavement material becomes RAP, which contains valuable asphalt binder and aggregate. With increased demand and limited aggregate and binder supply, HMA producer have began using RAP as a valuable component in HMA. As a result, there has been a renewed interest in increasing the amount of RAP used in HMA. While several factors influence the use of RAP in asphalt pavement, the two primary factors are economic savings and environmental benefits [4] [5].

In general, there is little difference in designing asphalt mixture with RAP compared to virgin asphalt mixtures until high RAP is used. However, the following issues should be considered when increasing RAP use: additional processing and quality control, characterizing RAP, changing the virgin binder grade, preparing materials for mix design, blending/comingling the virgin and RAP and performance [4]. The mix design procedure is expected to be an adaptation of AASHTO R 35, Superpave Volumetric Design for Hot-Mix Asphalt. The mix analysis procedure is expected to include performance-related test and key criteria to address permanent deformation, fatigue cracking, low-temperature cracking and moisture susceptibility and identify any promising method procedure developed to access the durability of HMA [5]. An important consideration in RAP management is when to keep RAP from a new source separate and when to combine RAP from different sources [4].

RAP may be obtained from several sources. The most common method is through "pavement milling operation", also known as cold planning (as mentioned before). Two other common sources of RAP are "full-depth pavement demolition" and "waste asphalt plant mix" [6] [4].

Milling is an important part of pavement rehabilitation used to removed any distressed upper layer(s) of existing pavement to a given depth. The process involves machine that grid, pick up, and load RAP into a truck for transportation. Full-depth pavement removal involves the use of heavy equipment to break the pavement structure into slabs. The slabs are then transported to the processing location where they are crushed and processed to a manageable size for recycling. Asphalt mix material that is produced and not used (i.e., "plant waste") is typically added to the unprocessed RAP stockpile or is kept in a separate stockpile for future processing [4].

In the case of pavement milling operations or waste asphalt plant mix are used commonly to produce a new asphalt concrete, but in the case of RAP, obtained from full-depth pavement demolition there is an amount of this material that can not be used to produce asphalt mix because is contaminated by soil.

In Japan, RAP obtained from full-depth pavement demolition is also known as "waste asphalt block". Waste asphalt blocks are usually transported to the processing plant and are crushed to use them as recycled asphalt aggregates. Figure 3 [7] shows the treatment that is carried out by the processing plant, over “waste asphalt blocks”, in an attempt to reduce its size, with the goal to be reused it as recycled asphalt aggregate.

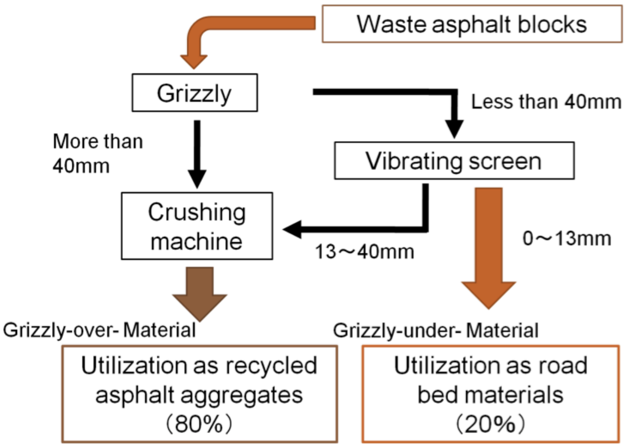

Fig. 3 Flow chart of crushing the waste asphalt block

First of all, waste asphalt blocks are fed into the grizzly, and then over size asphalt blocks (greater than 40 mm) are carried to the crushing machine. Crushed asphalt blocks are called “Grizzly-over-materials” (GOM), and generally, they can be used as recycled asphalt aggregates, because they satisfy the required standard values for Content of Asphalt (measured in % with respect to the total mass), Needle Penetration for Asphalt (measured in 1/10mm, that is, every unit is ten times smaller than a millimeter) and Amount of Soils (measured in % with respect to the total mass) shown in Table 1 [8].

Under size asphalt blocks (less than 40 mm) are carried to the vibrating screen. Over size materials on the vibrating screen are fed into the crushing machine and used as recycled asphalt aggregates. Under size materials, which pass through the screen, are called “Grizzlly-under-materials” (GUM) [9]. In the case of GUM, they can not be used as recycled asphalt aggregates to produce new asphalt concrete because most of them do not satisfy the required value for amount of soils shown in Table 1. When pavement rubble (RAP from full-depth pavement demolition) is contaminated with underlying layers and soil, it is better for this material to be crushed and used as a shoulder or base material than used in an asphalt mixture [6]. Therefore, the expensive substances in the GUM (aggregate and asphalt binder) are reused inappropriately, because they are used as if they were inexpensive materials. But, if the soil content in GUM can be reduced to less than 5% (standard value), they can be used as recycled asphalt aggregates to produce new asphalt concrete. Hence, it is necessary to create an alternative procedure, to process the recycled asphalt aggregates that can not be used in asphalt mix production, due to high soil content, avoiding to use them as a shoulder or base material in the road.

Table 1 Quality of recycled asphalt mixture

Items	Content of asphalt (%)	Needle penetration for asphalt (25°C) 1/10mm	Amount of soils (%) (less than 75μm)
Value of standard	More than 3.8	More than 20	Less than 5

In Japan, every year a large amount of waste asphalt blocks are obtained from road reparation. For example, according to the statistics in 2008, the amount of waste asphalt blocks was about 19 220 000 tons, 80% of this amount was GOM and it was used as recycled asphalt aggregates, but the remaining 20% was GUM and it was used as roadbed materials although they contain a large amount of asphalt [7]. Then, from this fact, it is difficult to say that effective recycling of waste asphalt blocks has been conducted.

RAP is a useful alternative to virgin materials because it reduces the use of virgin aggregate and the amount of virgin asphalt binder required in the production of hot mix asphalt (HMA). The use of RAP also conserves energy, lowers transportation costs required to obtain quality virgin aggregate, and preserve resources. Ultimately, recycling asphalt creates a cycle that optimizes the use of natural resources and sustains the asphalt industry [4]. The most economical and optimal use of RAP is in asphalt mixture [4], [10]. Therefore, the usage of GUM, as a recycled asphalt aggregate to produce asphalt concrete, constitute the best option for this material. Then, it is necessary to reduce the soil content in GUM, to use it as recycled asphalt aggregate.

One way to reduce the amount of soil in GUM is to decrease the mesh size of the vibrating screen. Nonetheless, at the same time, the reduction of mesh size in the vibrating screen increases the possibility of clogging in a short time. Consequently, most of the processing plant in Japan use vibrating screen with 13 mm mesh size empirically to avoid the clogging of the screen. From this situation, it is necessary to find another way or create a screenless equipment to reduce the soil content in the asphalt material to process.

1.2 Previous researches and objectives of this study

In 2009, the Takahashi Laboratory (Tohoku University, Graduate School of Environmental Studies) began the development of screenless equipment for high-level utilization of waste asphalt blocks containing roadbed materials. The main objective of this new equipment was to reduce the soil content in GUM to less than 5% [11].

As mentioned before, the usage of screens in the new equipment is not adequate for its good performance, because clogging can easily occur. As a result, aerodynamic force was used to remove the fine soil particles from the surface of the coarse aggregate that make up the GUM.

First of all, a horizontal pipe was tried as a main component of the equipment as shown in Figure 4, while GUM were moved through this tube the soils were removed by the air force. This first version of the apparatus had the following concept of work: GUM were fed into the pipe from the upper part; at the same time compressed air was supplied into the pipe, from the left side to the right side, to disperse and to transport the recycled asphalt aggregate downstream, that is, from left to right. From previous equipment activity, a certain amount of dispersed fine soil particles should arise inside the tube, and these fine soil particles would be sucked by the suction machine and removed from the surface of the coarse aggregate that make up the GUM. But the concept explained before , did not work well, because of the wide size distribution of GUM.

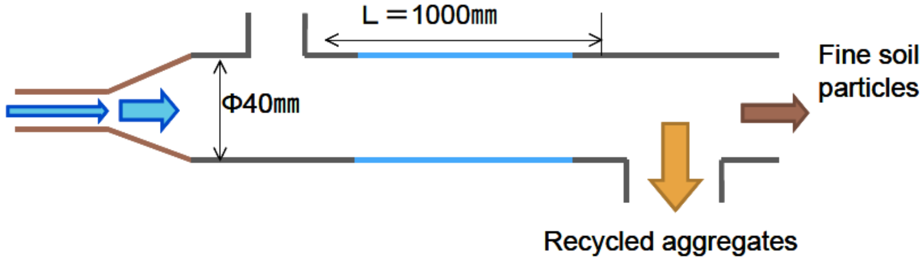

Fig. 4 Schematic diagram of initial equipment using a horizontal pipe.

When the air velocity was decreased, the air did not have enough aerodynamic force to move the coarse aggregate that makes up the GUM, therefore the materials settled down in the pipe. On the contrary, if stronger aerodynamic force was supplied into the pipe to transport all GUM, most of them were blown off the pipe. Therefore, the proposed new equipment, to separate the fine soil particles from the surface of coarse aggregates that makes up the GUM, was not effective.

Afterwards, the first design of the apparatus was changed; the horizontal pipe was placed in a diagonal direction, with the goal to utilize the gravitational force and to reduce the air velocity. The inclination angle of the pipe was changed from 0° to 40°. This slope of the pipe was chosen based on the angle of repose of GUM. That angle of repose was 35°, therefore, that choice was made with the goal to assure that when the GUM were fed into the pipe, they could move easily through the tube with low air velocity. Figure 5 shows a schematic diagram of the proposed experimental apparatus.

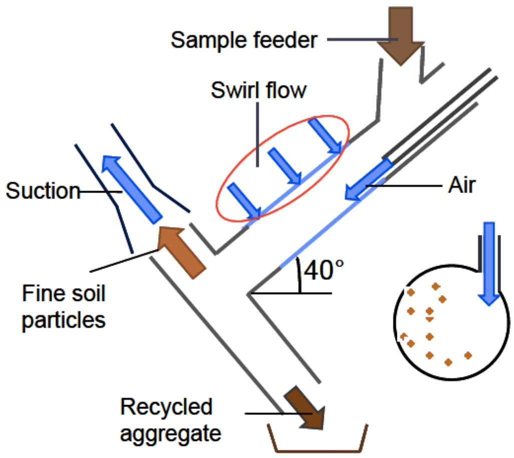

Fig. 5 Schematic diagram of apparatus

At the end of the pipe, that is, at its lowest point, a suction machine was placed in the equipment, with the goal to suck up the fine soil particles. The air in the same direction of the pipe had the purpose of helping the movement of the GUM; and the swirl air flow which was blown into the pipe from the tangential direction was expected to separate the fine soil particles from the surface of the coarse aggregates that make up the grizzly under materials. The length of the pipe (falling section) was set at 0.5m, 1.0m and 1.5m and the inner diameter of the pipe was 40 mm. Figure 6 shows a photograph of the experimental apparatus.

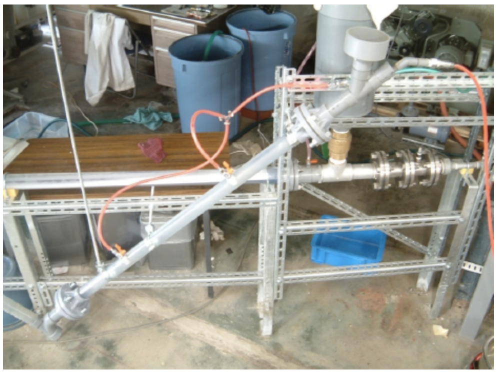

Fig. 6 Photograph of Experimental proposed equipment.

The water content of the GUM affected the experimental results. Then, the experiments were carried out under 1%, 3% and 5% of water content.

In the apparatus that was used to carry out the experiments, two kind of air compressors were used; the first one was a large compressor and the second one was a small compressor. The large compressor was used to blow the air inside the equipment in the same direction of the material movement, to facilitate the transportation of the GUM through the pipe. The small compressor was used to produced a swirl air flow, and the total flow rate was always constant regardless of the number of blowing places.

From this last proposition of separation apparatus, several conclusions were drawn from the experimental results, for instance:

1. The swirl air flow was effective to reduce the soil content in the GUM.
2. Soil content increased in the processed GUM by the separation equipment when the water content increased.
3. The effect of the length of falling section on the amount of content in the processed GUM was not significant.
4. The increase of the suction places in the separation equipment increased the equipment performance.

After the experiments in the Takahashi Laboratory, a full scale equipment was designed in the Sendai Asphalt Plant of Maeda Road Construction Co., Ltd. The design of this equipment was carried out taking into consideration the conclusions drawn from the experimental results of the Takahashi laboratory equipment; another factor considered in the design was the space in the recycled asphalt plant.

The full scale equipment has 4 suction opening and 10 blowing nozzles for swirl air flow. Figure 7 and Figure 8 shows a photograph and a schematic diagram of the full scale equipment. As shown in the Figure 8, the horizontal length and the height of this equipment were both 4 meters, then in this case the slope of the pipe was about 45°. The diameter of the main pipe was decided to guarantee a proper productivity of the equipment to process the recycled asphalt pavement, for that reason the diameter was increased 12.5 times establishing a comparison with the diameter of the equipment in the laboratory, so the diameter of the pipe in the laboratory was 40 mm, then the diameter of the pipe in the full scale equipment was 500 mm (50cm).

Fig. 7 Photograph of the full-scale equipment.

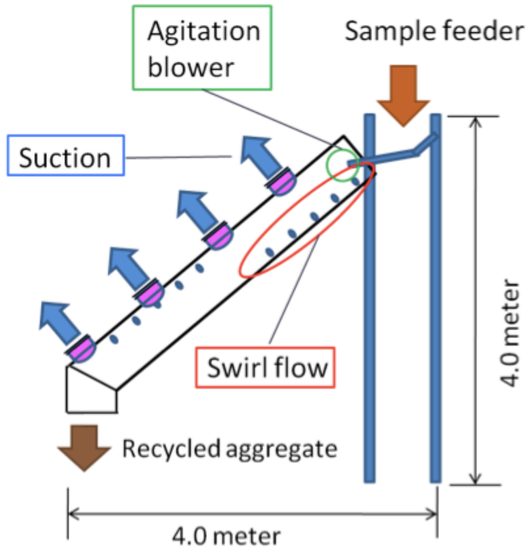

Fig. 8 Schematic diagram of full-scale equipment.

Other characteristics established in the equipment were as follow: the capacity of the suction machine was $42m^3$/min and its static pressure was 1.47kPa, the blowing capacity of the compressor was $5.2m^3$/min, the vibrating feeder was set in the sample feeder to prevent blockage of the GUM. The processing time inside the full scale equipment was controlled by changing the frequency of the vibrating feeder.

As mentioned before, it was confirmed that plural suctions were effective to reduce the soil content on the surface of the coarse aggregate that make up the GUM, then the full scale equipment was designed so that it had 4 suction openings. However, this system had one suction machine, and the preliminary experiment showed that this suction machine did not have enough power to use 4 suction openings. Therefore, as shown in Figure 9, the lower suction openings were closed.

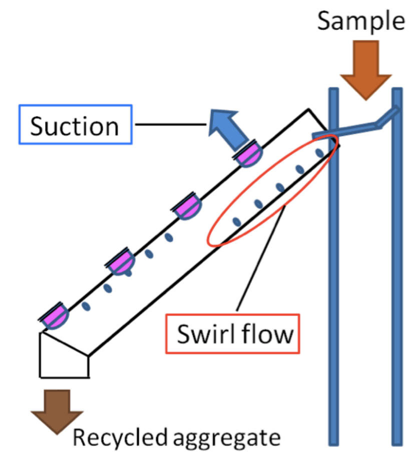

Fig. 9 Schematic diagram of full-scale equipment with 1 suction opening.

In the case of the experiments that were carried out using the full scale equipment, it was difficult to control the water content of the GUM, because the volume of this material was too large. So, this experiment was carried out under about 1% of water content and the processing time was controlled by the frequency of the vibrating device located at the bottom of the feeder.

The capacity of suction of the full scale equipment was defined by the ratio of the weight of the materials sucked by the suction machine compared to the initial weight of the GUM in the feeder. The processing time was defined by the time in which 25kg of GUM go through the apparatus. The frequency of the vibrating device was set at 60, 30, 25, 20 and 15 Hz and the processing time was 25, 50, 75, 100 and 175 second for each frequency, respectively.

The main conclusion from the experimental results that were drawn from the full scale equipment in the asphalt plant was the following:

1. The capacity of suction of the full scale equipment increased while the processing time inside the equipment increased too.

From the process of designing the separation equipment and the experiments that were carried out in the laboratory and in the asphalt plant, several conclusions have been reached. Numerous time, the processed GUM obtained after the treatment inside the tested equipment in the laboratory and in the asphalt plant met all quality standards, including the required value for amount of soils.

However, the specific processed GUM mentioned above met the required value for amount of soil, after been fed several times into the equipment. Although the proposed separation equipment was able to produce a GUM that met the required value for amount of soil, it is necessary to improve its performance.

As mentioned above, the best usage for waste asphalt concrete is to recycle the total amount of waste asphalt blocks as recycled asphalt aggregates. For that reason, it is very important to improve the proposed separation equipment and then guarantee a sustainable road construction. Therefore, the main objectives of this study are the follows:

1. To re-design the screenless separation equipment with the goal to improve its performance.
2. To define the main factors those decide the equipment performance.
3. To obtain a numerical model to predict the equipment performance.

1.3 Literature review

There are many researches around the world those demonstrate the importance of increasing the usage of recycled asphalt aggregate. That is, to produce new asphalt concrete using recycled asphalt aggregate. In order to highlight and understand the importance of recycling of asphalt mixture in many countries a literature review was carried out.

Kawakami, Nitta, Kanou, & Kubo [12] studied on CO2 emissions of pavement recycling methods. They established a comparison between the CO2 emissions when virgin aggregates are used and recycled aggregates are used with cut and overlay. The results showed that, the total emissions were less when recycled aggregate were used, because the quantity of asphalt and aggregates transported were reduced, this fact is a good point for using recycled aggregate to reduce the CO2 emission, another necessary information should be the relationship between the asphalt content in recycled aggregate and the amount of CO2 emission reduction.

McDaniel, Soleymani, & Shah [13], carried out a research on use of reclaimed asphalt pavement (RAP) under SuperPave specifications, with the objective to consider the usage of recycled asphalt aggregate. They concluded, using RAP, acceptable SuperPave mixture could be designed with up to 40% or 50%. Excessively fine RAP gradations may be limit the amount of RAP that can be incorporated in a new SuperPave mixture. Depending on, the quality of the aggregates in the RAP and the traffic level, even higher RAP contents may be feasible. It is important to notice that should be considered the effect of temperature (weather conditions) on SuperPave mixture performance.

Department of Transport and Main Roads Specifications [14] studied on transport and main roads specifications and recycled materials for pavements. They stated recycled materials for pavement shall not contain tar binder and should be free of contaminants such as clay, organic matter or any other deleterious material. Sometimes, it is a little bit difficult to avoid contamination; therefore it is necessary to state the usage of contaminated recycled materials depending on the contamination.

Copeland [4] carried out a research on RAP in asphalt mixtures and state of the practice. He reported, state of transportation department and contractors are reassessing the economic and environmental benefits of allowing higher percentages of RAP in premium pavements and asphalt surface while also maintain a high-quality, well-performing pavement infrastructure.

It is good to notice that in the process of reassessing the economic and environmental benefits of using RAP, it is convenient to consider the cost of maintenance of the road.

Eller & Olson [15], studied about recycled pavements using foamed asphalt in Minnesota. They reported, Falling Weight Deflectometer (FWD) data analysis reveals that the recycled pavement layer, when use cold in-place and full-depth reclamation, develops a relatively uniform strength despite the high variability inherent in most low-volume roads. Core data, indicates that the foamed asphalt forms a cohesive matrix when mixed with the fines from the reclaimed materials. Another fact to be consider in this research is the influence of particles size distribution variability on performance of recycled pavement layers.

European Asphalt Pavement Association [16], published arguments to stimulate the government to promote asphalt reuse and recycling. They conclude, in order to stimulate recycling, it is important to have a government policy which sets the conditions for the asphalt industry to invest in equipment to recycle RAP. Another idea to stimulate the usage of recycled materials should be reduce the annual fee that companies have to pay if they use recycled materials.

Molenaar, Mohajeri, & van de Ven [17], carried out a research on, design of recycled asphalt mixtures. They advised, the currently used mixture design procedure should be modified taking into consideration the specific characteristics of the materials to be used in the design. Besides, should be considered the characteristics of the technology in the production of recycled asphalt mixture at construction site.

Tabaković, Gibney, McNally, & Gilchrist [18], studied on influence of recycled asphalt pavement on fatigue performance of asphalt concrete base courses. Researcher stated, the laboratory test have shown that the introduction of RAP to the binder course mix resulted in an improvement in all mechanical properties. In particular, it was found that the mix containing up to 30 % RAP, displayed improved fatigue resistance relative to the control mix manufactured from virgin materials. Another fact to be considered in this research should be the durability of recycled asphalt pavement in a test section on service.

Su, Hachiya, & Maekawa [19], carried out a research on laboratory investigation of possibility of re-recycling asphalt concretes. The result from this research indicate that, asphalt extracted from aged Recycled Asphalt Concrete can be used again and that Re-Recycled Asphalt Concrete offers similar performance to New Asphalt Concrete when using straight asphalt and slightly lower performance in case of using modified asphalt. It is also necessary to consider in this research the performance of re-recycling asphalt concrete in a test section on service.

Zeng, Wu, & Zhang [20], studied the mixing and compaction temperature of reclaimed asphalt pavement. It is noted that although the equi-viscous-volumetric principle was developed using warm mix asphalt (WMA) of 100% RAP and Marshall compaction procedure (method for determining mixing and compaction temperatures of WMA). It is expected that the method should provide valuable reference for WMA with other percentage of RAP, other types of WMA additive, or other procedures of compaction. WMA is a very popular practice in road field because it is necessary less energy to produce it than in the case of hot mix asphalt. So, it is very important to consider the production of WMA using the RAP as a recycled asphalt aggregate. Besides, should be considered in this procedure the influence of asphalt content in the reclaimed asphalt pavement on the warm mix asphalt performance containing 100% RAP.

Carruth & Mejías-Santiago [21] studied on hot in-place asphalt recycling for small repairs on airfield in remote setting. One alternative for small-sized repairs on aged asphalt concrete (AC) airfield in remote locations is using Hot In-place Recycling (HIR) techniques. Typically HIR uses some amount of virgin material, but the study described in this paper deals specifically with the reuse of existing material and eliminates the need to bring in or store any virgin repair materials on-site. This new technique related with HIR is convenient to decrease even more the cost of repairing road activities, but the characteristics of the existing material should be analyzed in detail taking into consideration the level of the traffic.

Gonzalo, Pérez-Jiménez, Miró, Martínez, & Botella [22], carried out an experimental study of recycled asphalt mixtures with high percentage of RAP. In this study, it was found that, higher RAP contents lead to increased stiffness, as shown by the results of stiffness modulus, dynamic modulus and IRT, also it was discovered that the fatigue laws of recycled mixtures and high modulus mixtures are very similar. It is necessary take into consideration the influence asphalt content in RAP on recycled mixtures performance because the asphalt binder content changes at construction site.

Praticò, Vaiana, & Iuele [23], studied about permeable wearing courses from recycling RAP for low-volume roads. They focused on obtaining permeable pavement by recycling high percentage of RAP derived from porous European mixes (PEMs) under realistic assumptions about RAP variability. This study concluded that, recycled mixes exhibited volumetric properties, mechanistic properties, and surface performance that substantially met the basic specification limits. Besides, should be considered this kind of research for high-volume road with different weather conditions.

Praticò, Vaiana, Iuele, & Puppala [24], carried out studies related with HMA sustainability, producing a recycled permeable mix that performs as well as the original porous mix. They examined the variability of RAP and a method for facing its consequences was proposed. It was concluded that, mechanical performance was adequate, recycling of porous European mixes could a proper way to achieve the environmental sustainability in pavement. It is also necessary to study how change the drainage capacity of these kind of mixtures on service.

Praticò, Vaiana, & Giunta [25], studied on pavement sustainability, using permeable wearing courses by recycling porous European mixes. The focused in strategies and procedure for recycling PEMs back to permeable wearing courses. In particular, a two-layer porous asphalt was considered to mitigate some disadvantage like: clogging, appreciable variation of volumetric, noise, texture, friction and permeability performance over time. Mixes with high RAP contents were produced and tested. Design and construction features, including mix design and mixing procedures, were addressed. Even the mechanical and environmental properties are promising, another characteristics should be analyzed like the durability of the mixture.

Praticò, Vaiana, Giunta, Iuele, & Moro [26], carried out studies related with the issues that arise at the end of PEMs's lifecycle, for example: RAP variability, uncertainties on the potential for high percentage recycling, potential for recycling a surface layer back to a surface layer. Based on the above mentioned facts, they concentrated the attention into the analysis of the of the feasibility of a two-layer porous asphalt by recycling from PEM-RAP, when highly variable RAP stockpile are involved. Materials selection was followed by mixtures production. Traditional and advanced tests on RAP and recycled mixes were carried out. RAP variability was examined and several trials were carried out. Mechanical performance was adequate and environmental compatibility was achieved. Functional performance resulted very promising. This kind of research should conducted under different weather conditions.

Praticò [27], studied the metric for management of asphalt plant sustainability. He focused on the design and validation of a method for assessing the sustainability of an asphalt plant. The method involves two levels of analysis: analysis of the architecture of the overall system (long-term analysis, based on lifecycle cost analysis, LCCA) and an asphalt plant scoring system (short-term analysis). An overall model was set up based on the synergistic consideration of different factors and interactions (long-term analysis). It was found in this research that, assessing the economic and environmental status of an asphalt production facility is crucial and that qualifications-based selection systems are a feasible solution, the method described in this study provides a tool to assess asphalt plant qualification at different levels of complexity. It is recommended also, to apply the mentioned analysis in developing countries, because most of the time they do not have the last technology.

Kuehl, Korzilius, & Marti [28], carried out an investigation related with RAP material. In this study they confirmed that variability of RAP materials in terms of gradation, asphalt content and asphalt characteristics or quality lead to variability in the characteristics and volumetric properties of the produced asphalt materials. Therefore, to control the variability of RAP materials and allow for increased percentages of RAP to be incorporated into new asphalt mixtures, good stockpile management practices is necessary. For instance, one key issue to address is elimination of contamination within RAP stockpile. Another characteristics to consider in RAP is the water content at construction site, because it is an important factor in asphalt mixture production.

Esenwa, Davidson, Kucharek, & Moore [29], carried out a study related with 100% recycled asphalt paving. A noteworthy from this research is that an emulsion consisting of fractions of asphalt cement as well as rejuvenating oil has been formulated for use in the design and construction of a 100% RAP asphalt mix. A laboratory method to determine the proper formation has also been developed and verified in the field. A trial section using this product, RE-II, with 100% aggregates, has been successfully built on Cedar Height Road in the City of North Bay. The initial results looked very promising. The test section will be monitored closely over the next few years to assess the field performance and modify the emulsion formulation as necessary to achieve optimum results. Besides, it is necessary to consider to build trial section under different traffic volume.

From all the researches mentioned above the researcher concludes that the usage of recycled asphalt material is very important for the environment and for the economy for every country. Every research was carried out using a recycled asphalt pavement or recycled asphalt aggregate that met the required standard in each country. Then, it is very important to guarantee a recycled asphalt material with the proper quality, to assure good properties in the recycled asphalt concrete produced using the recycled asphalt material.

Therefore, to develop a new separation equipment to guarantee the proper quality of the recycled asphalt aggregate is one of the most significant activity for researcher and professional staff related with road engineering at present, because, that is the only to assure a sustainable road construction. On the other hand, sustainable road construction means, not only to recycle the total amount of waste asphalt blocks, obtained from road reparation, besides, it is necessary to keep in mind that it is important to carry out a suitable usage of waste asphalt blocks.

1.4 Structure of the thesis

Chapter 1. "Introduction", describe the situation of recycling waste asphalt blocks in Japan and explain why arise the necessity to start the development of a screenless separation equipment at Takahashi Laboratory from 2009. Taking into consideration those facts, it is proposed the main objectives of this research. In addition, a detailed literature review was carried out in an attempt to prove the importance of increasing the usage of waste asphalt blocks as a recycled asphalt aggregate to produce new asphalt concrete.

Chapter 2: "Experimental study on Movement of Grizzly Under Materials", explains the movement analysis of GUM. In this explanation, it is shown the process in the laboratory to obtain frequencies, amplitudes and slopes of the pipe that guarantee a proper movement of the GUM through the pipe, with different water content (1%, 3% and 5%). Besides, the proposed changes in the screenless separation equipment are also explained.

Chapter 3: "Experimental Study on Soil Reduction Content in Grizzly Under Materials", analyzes the performance achieved by the screenless separation equipment setting in the experiments the conditions obtained in Chapter 2. The experimental conditions were the same, in case of 3% and 5% of water content in the material to process. On the other hand, the experimental condition to process the GUM with 1% of water content were different from those related with 3% and 5%. A comparison between the experimental results related with 3% and 5% of water content in GUM was carried out. Besides, in case of 1% of water content in GUM, experimental results related with 20° and 25° of pipe inclination angle were compared each other.

Chapter 4: "Experimental Study on Soil Reduction Content in GUM Setting the Same Experimental Condition", shows the characteristics of two different samples of GUM (without soil) and two different samples of soil, which were used to produce four different designed mixtures of GUM (without soil) and soil at the laboratory. Each designed mixture was used to carry out experiments setting the same conditions (setting temperature at 15°C or 25°C), changing only the water content in the material to process. Besides, a statistical analysis was carried out with the target to discover if difference arise in the equipment performance, when change the materials to process and set in the laboratory 15°C or 25°C.

Chapter 5: “Simulation on Soil Reduction Content in GUM”, shows the procedure to obtain a numerical model to simulate the equipment performance. In the process to obtain the mentioned model, the specific characteristics of GUM, soil and the experimental conditions were considered independent variables and the rate of suction of the equipment was considered the dependent variable. After obtaining the numerical model, it was carried out a simulation of the equipment performance where the whole independent variables were changed, in an attempt to know the behaviour of rate of suction.

In Chapter 6: “Conclusions and recommendations”, it is shown the general drawn conclusion, taking into consideration the whole experimental results in this study. It was tried to summarize the most important research experiences in this chapter. Furthermore, several recommendations were proposed in an attempt to highlight important aspect to take into consideration to continue with this research in the future.

CHAPTER 2 EXPERIMENTAL STUDY ON MOVEMENT OF GRIZZLY UNDER MATERIALS

CHAPTER 2 EXPERIMENTAL STUDY ON MOVEMENT OF GRIZZLY UNDER MATERIALS

2.1 Proposed changes in the experimental equipment

Conclusions from previous experiments demonstrate that if the processing time inside the equipment is increased, it is possible to increase the equipment performance. That is, the equipment is able to reduce the soil content in the GUM as much as possible. One way to increase the processing time of the recycled material inside the apparatus is to decrease the slope of the pipe, but if this parameter is decreased to less than 35° (angle of repose of the GUM), it will be necessary to add a vibration device to the equipment to move the GUM through the pipe. Therefore, the slope of the pipe is an important factor to take into consideration to carry out the experiments.

The decrease of slope of the pipe and the addition of a vibration device to the separation equipment represents the process of re-designing this apparatus to improve its performance, taking into consideration previous experiences and experimental results.

Other changes proposed in the process of re-designing the separation equipment were the following:

- The air inside the equipment that flows in the same direction of the pipe is removed. Previously it came from the large compressor and had the objective to facilitate the transportation of the recycled asphalt aggregate through the pipe. From now on, the added vibration device has the goal to guarantee the movement of the GUM through the pipe.
- Previously, the swirl air flow which was blown into the pipe from the tangential direction and was expected to separate the fine soil particles from the surface of the coarse aggregate that make up the GUM. Since this swirl air flow from now will come from the large compressor, a stronger force will be obtained and this fact will increase the probability of separating the fine soil particles from the surface of the coarse aggregate that make up the GUM.

Then, after finishing those changes in the apparatus, the first step to carry out the experiment in the laboratory is to know the movement properties of the GUM. To know the properties mentioned before, it is very important to process the GUM with the equipment that is being developed. Also, it is possible to check the productivity of the apparatus in the laboratory, this parameter measures the amount of kilograms that the equipment is able to process per hour (kg/h), then with this information the productivity in the asphalt plant using a full scale equipment can be estimated.

Productivity of the equipment and movement properties of the GUM are closely related with each other. These data are very important for planning the production of asphalt concrete in the asphalt plant. The more productivity to process the GUM the more production of asphalt concrete. But when the process inside the equipment is finished, the soil content in the recycled asphalt aggregate should be less than 5 %. If this requirement is met by the processed materials, they can be used as recycled asphalt aggregates to produce new asphalt concrete.

Taking into consideration this restriction mentioned above, it is necessary to determine the higher productivity of the equipment that has been developed, that guarantees to match with the Japanese Standard Specification (soil content less than 5 %). Besides, it is necessary to know the productivity of the equipment and movement properties of the GUM with different water content, because this parameter has a great influence on the properties of the metarials to process. Water content in the GUM changes depending on the weather; in the rainy season this parameter increases but in the dry season decreases. This parameter represents the percent of water mass inside the GUM with respect to the total mass; water content will be measured in percent (%).

If a vibration device is added to the apparatus, it is necessary to take into consideration the frequency and the amplitude of the vibration to the movement analysis of the GUM. Frequency will be measured in revolution per minute (RPM) and amplitude will be measured in centimeters (cm).

Therefore, in the first stage of this study on recycling of asphalt concrete (movement analysis), several factors should be considered, for instance: slope of the pipe (°), water content (%), frequency (RPM) and amplitude (cm).

2.2 Experimental apparatus

The experimental study on movement of GUM after establishes the new proposed set of characteristics in the equipment was carried out in Takahashi Laboratory. The newly proposed screenless separation equipment was composed by a large compressor, a suction machine, a vibration device and a main pipe.

The large compressor has a maximum capacity of 250 L/min; it was used to blow the swirl air flow into the pipe from a tangential direction with the purpose to separate the fine soil particles from the surface of the coarse aggregates that make up the GUM; Figure 10 shows a photograph of the large compressor.

Fig. 10 Air large compressor.

The suction machine was used to suck the removed fine soil particles from the surface of the coarse aggregates that make up the GUM; Figure 11 shows a photograph of the suction machine.

Fig. 11 Suction machine.

The vibration device was used to produce a controlled vibration in the equipment, changing its amplitude and frequency. The vibration device is composed by two elements; the first one is a motor and the second one is a cam; Figure 12 shows a photograph of the motor and the cam to produce 5 cm of amplitude.


Fig. 12 Motor and cam (vibration device)

The main pipe of the equipment was used to support the movement of the GUM and the separation process of the fine soil particles from the surface of the coarse aggregate that make up the GUM. Figure 13 shows a photograph of main pipe of the equipment.

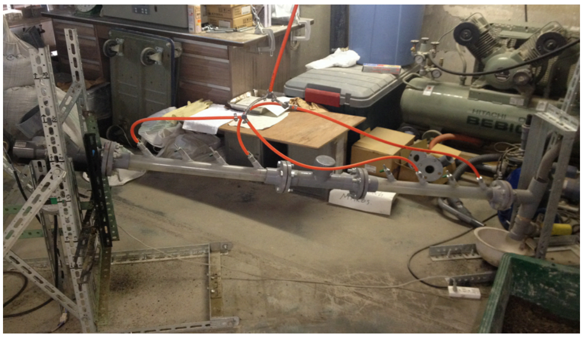

Fig. 13 Main pipe of the equipment.

Figure 14 shows a schematic diagram of the newly proposed screenless separation equipment with its main characteristics.

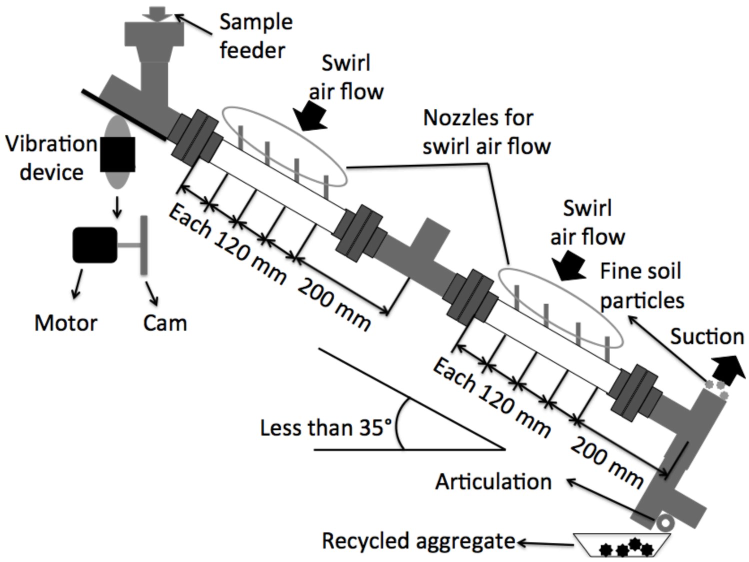

Fig. 14 Schematic diagram of the newly proposed separation equipment.

2.3 Experimental procedure

The experimental study on movement of GUM was carried out as follows:

1. To prepare a sample of GUM with 1% of water content (150grams).
2. To set the slope of the pipe at an angle lower than 35°, this parameter was changed in every experiment, taking into consideration experiences from previous experiments.
3. To start the large compressor of the equipment.
4. To start the vibration device of the equipment, changing its frequency and amplitude in every experiment.
5. To measure the time that the equipment needed to move 150 grams of GUM through the main pipe.

6. To estimate the amount of materials that the equipment could move per hour, after obtaining the time measure in step 5.
7. To repeat from step 1 to step 6 preparing the sample of GUM with water content of 3% and 5%.

2.4 Experimental specimens used in this study

To carry out the experimental study on movement of GUM in Takahashi Laboratory were used recycled asphalt aggregates form Sendai Asphalt Plant of Maeda Road Construction Co., Ltd; and most of them did not match the required value for Amount of soils shown in Table 1 [8]. Figure 15 shows a photograph of a sample of GUM.

Fig. 15 Sample of grizzly under materials used in the experiment.

2.5 Results and discussion.

2.5.1 Experimental results (WC = 1%)

Figure 16, 17 and 18 show graphically the amount of materials (productivity) with water content of 1% that the equipment was able to process in one hour, with slope of the pipe equal to 15°, 20° and 25° respectively. In every figure the frequency and the amplitude were changed. S = slope of the pipe; WC = water content; P = productivity; F = frequency; A = amplitude

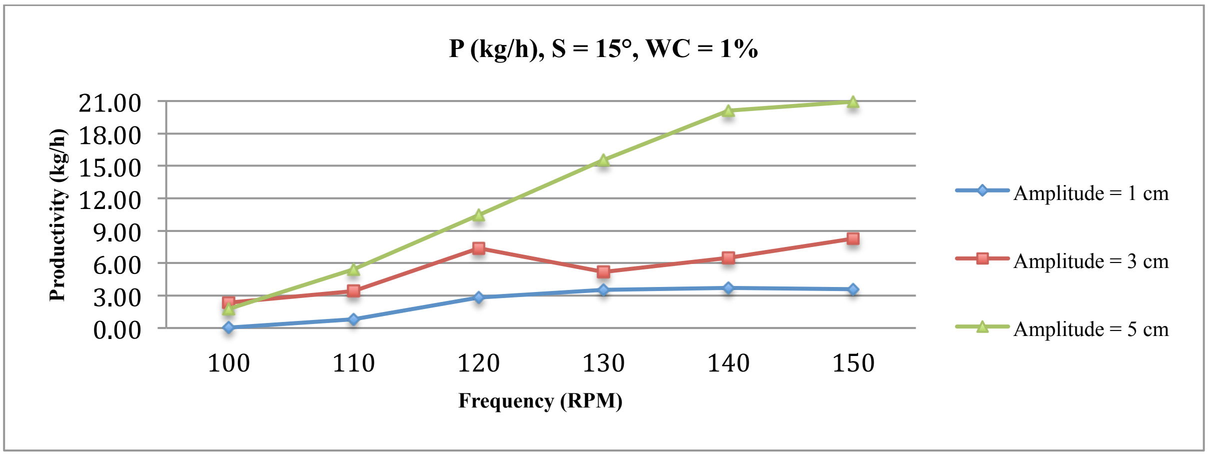

Fig. 16 Relationship between Productivity and Frequency (S=15°, WC=1%)

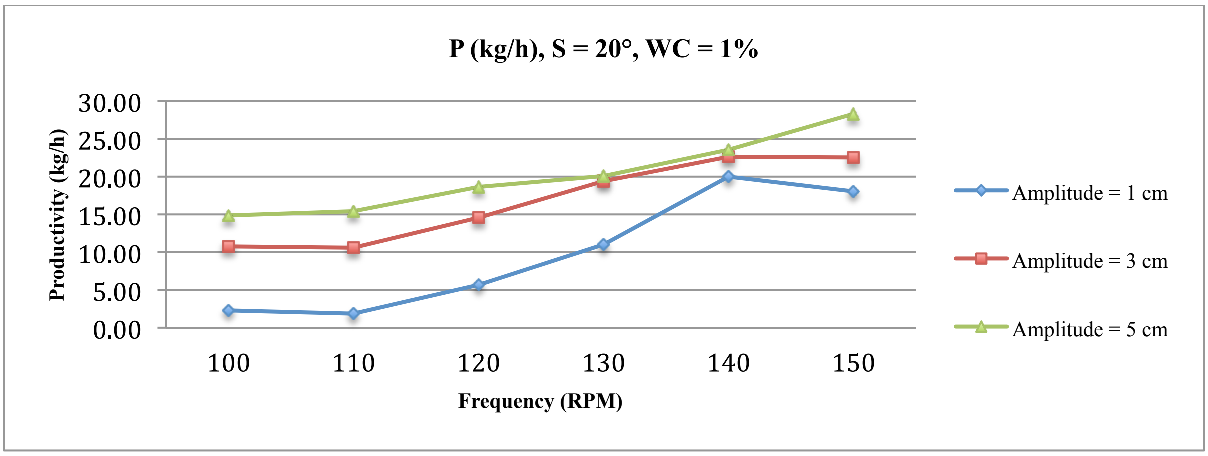

Fig. 17 Relationship between Productivity and Frequency (S=20°, WC=1%)

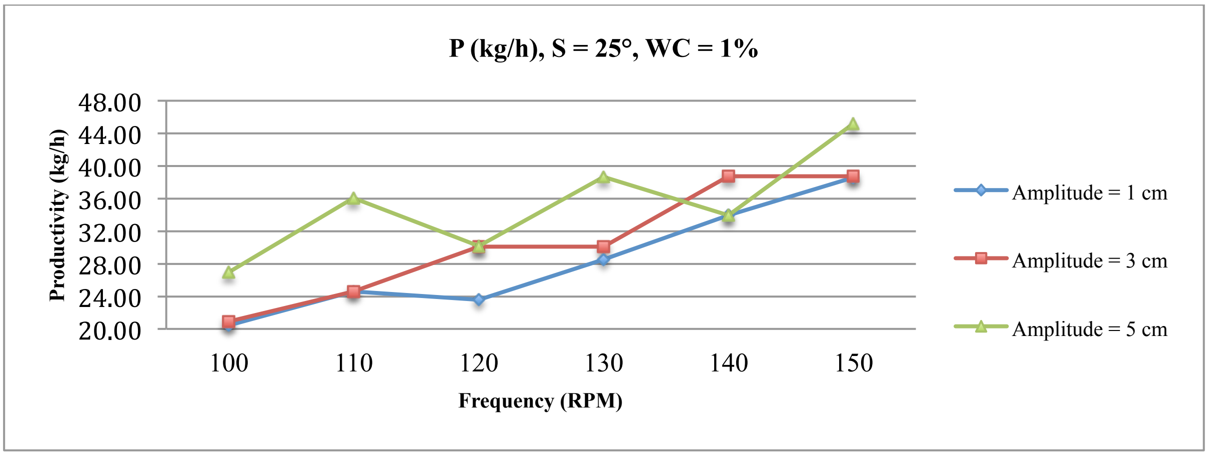

Fig. 18 Relationship between Productivity and Frequency (S=25, WC=1%)

Figure 19, 20 and 21 also show the productivity of the apparatus, but this time from a different point of view, because in every figure the frequency and the slope of the pipe were changed.

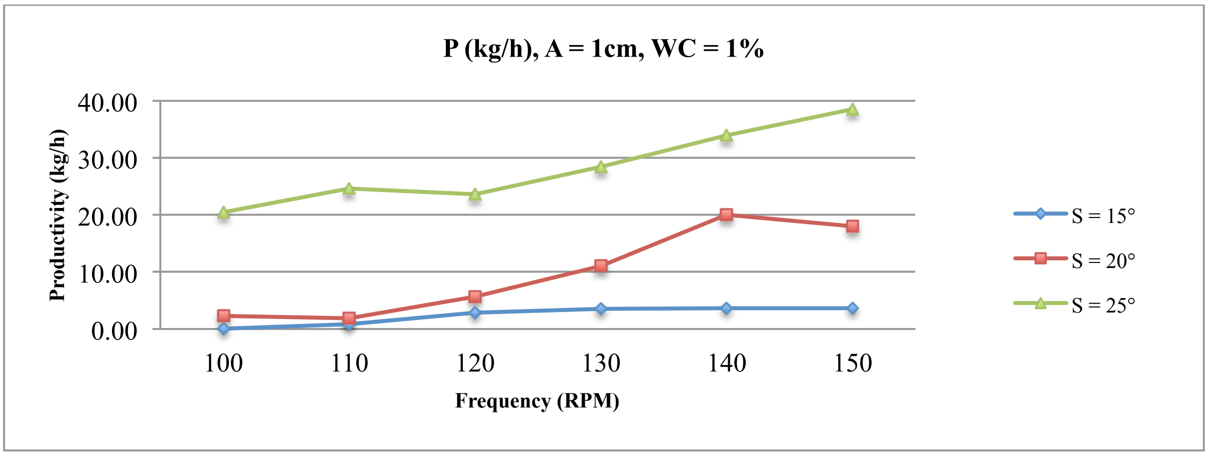

Fig. 19 Relationship between Productivity and Frequency (A=1cm, WC=1%)

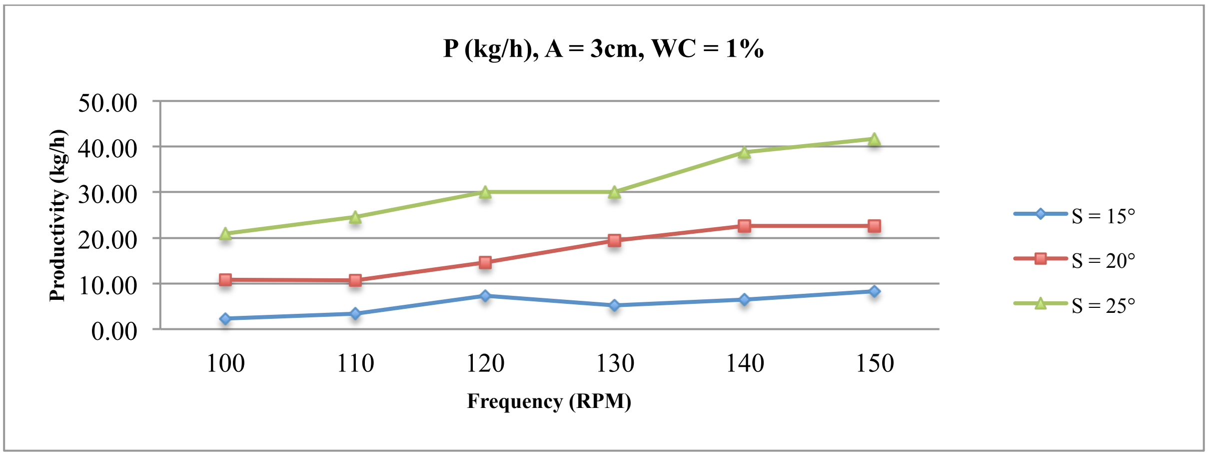

Fig. 20 Relationship between Productivity and Frequency (A=3cm, WC=1%)

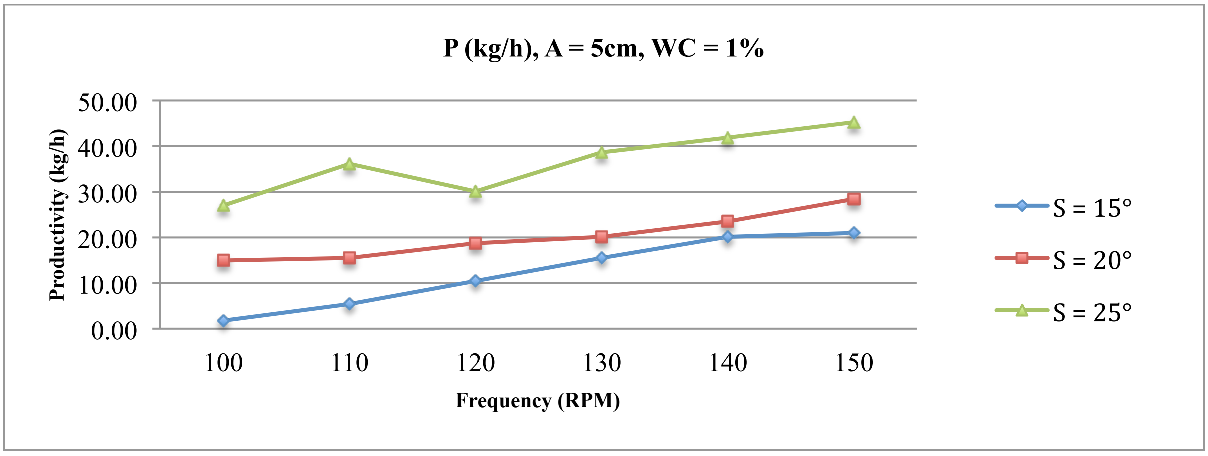

Fig. 21 Relationship between Productivity and Frequency (A=5cm, WC=1%)

The experiments were carried out by changing frequency, amplitude and slope of the pipe, with the goal to check the behavior of the GUM. Experimental results from Figure 16, 17, 18, 19, 20 and 21 demonstrate that while the frequency was increased the amount of material that the equipment was able to process in one hour generally increased.

Also, establishing a comparison among the amount of material that the equipment was able to process in one hour for each slope of the pipe, it was possible to conclude that while the slope of the pipe was increased, productivity also increased, regardless the frequency. Besides, establishing a comparison among the amount of material that the equipment was able to process in one hour for each amplitude, it was possible to conclude that while amplitude was increased, productivity generally increased, regardless the frequency.

In Addition, it was noticed that if the productivity of the equipment in the laboratory was more than 30 kg/h, the processing time of GUM inside the apparatus was somewhat short. Besides, productivity was lower when keeping constant slope of the pipe at 15°, amplitude of

1 cm and changing frequency; higher productivity was obtained keeping constant slope of the pipe at 25°, amplitude of 5 cm and changing frequency.

On the other hand, in most cases it was possible to increase even more the equipment productivity when the slope of the pipe was changed from 20° to 25° than when it was changed from 15° to 20°.

Higher productivity was obtained in every slope of the pipe with frequencies of 130 RPM, 140 RPM and 150 RPM. But the processing time of GUM inside the apparatus with productivity of more than 30 kg/h, was somewhat short. Therefore, the experiments were planned to start measuring soil content in the GUM with the frequencies mentioned above and slope of the pipe at 20°. Figure 22 shows the set of characteristics that will be established in the equipment to start the experiments with water content equal to 1% in the GUM.

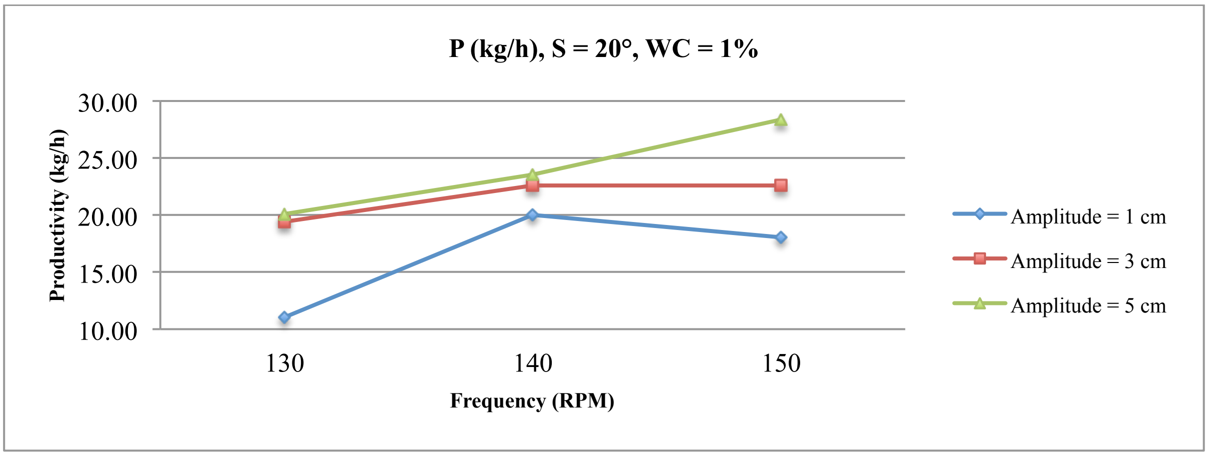

Fig. 22 Relationship between Productivity and Frequency (S=20°, WC=1%)

2.5.2 Experimental results (WC = 3%)

Figure 23, 24 and 25 show graphically the amount of materials (productivity) with water content of 3% that the equipment was able to process in one hour, with slope of the pipe variations of 20°, 25° and 30° respectively. In every figure the frequency and the amplitude were changed.

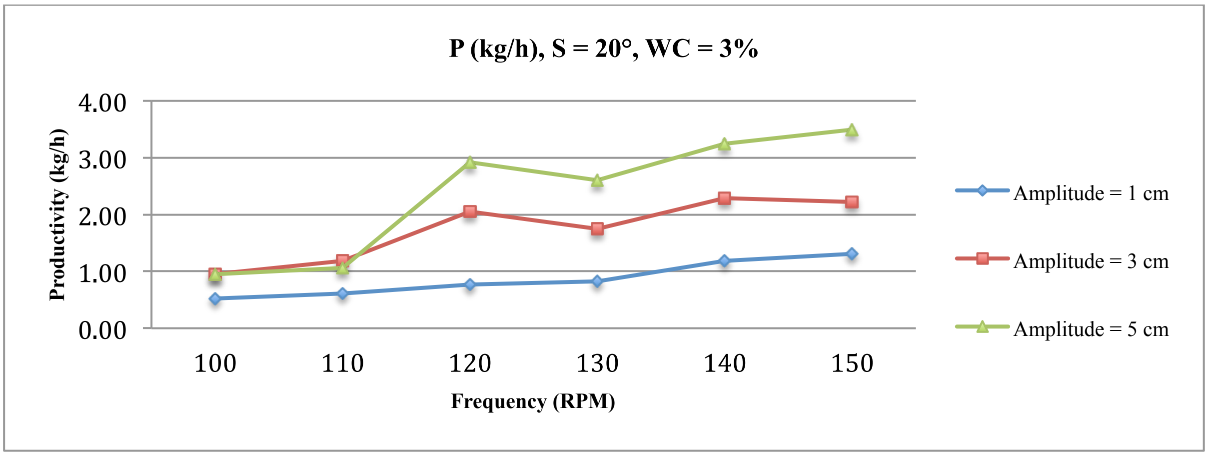

Fig. 23 Relationship between Productivity and Frequency (S=20°, WC=3%)

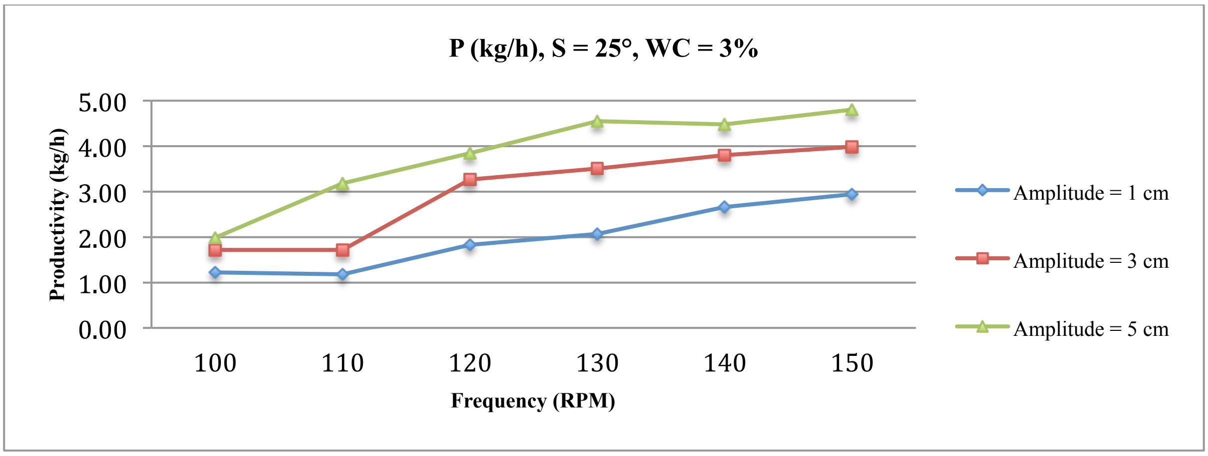

Fig. 24 Relationship between Productivity and Frequency (S=25°, WC=3%)

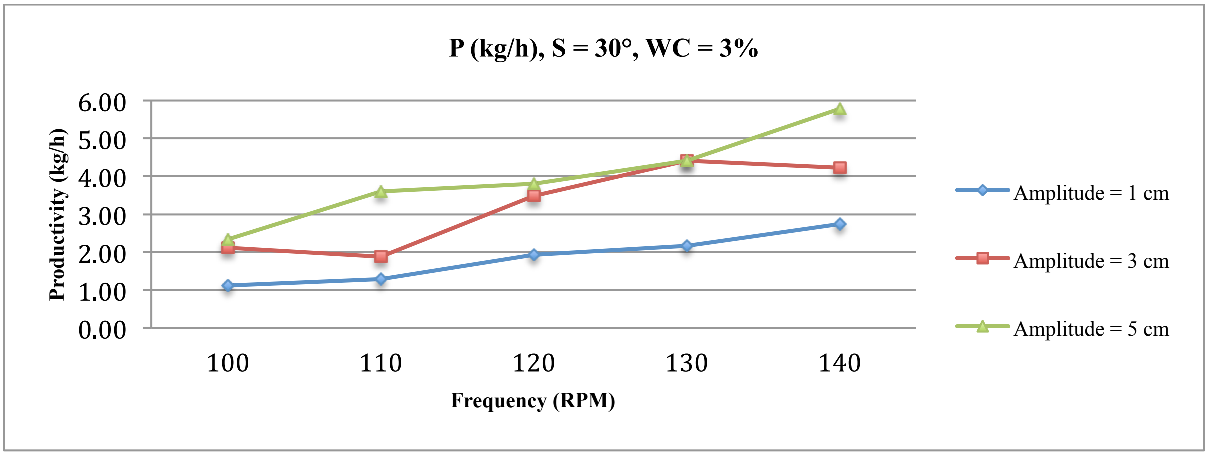

Fig. 25 Relationship between Productivity and Frequency (S=30°, WC=3%)

The experiments were carried out by changing frequency, amplitude and slope of the pipe, with the goal to check the behavior of the GUM. Experimental test demonstrate that in case of S = 20° and WC = 3% (Figure 23); when GUM were fed into the equipment, the materials started the movement through the pipe but one or two seconds later there was an amount of the material to process, that did not move and remained at the beginning of the pipe.

Besides, in case of S = 25° and S = 30° with WC = 3% (Figure 24 and 25 respectively); when GUM were fed into the equipment, the materials started the movement through the pipe but after one or two seconds there was an amount of the material to process that did not move at the beginning of the pipe. However, the coarse aggregates that make up the GUM generally had a processing time inside the equipment of less than 20 seconds and the fine aggregate that remained at the beginning of the pipe started a very slow movement about one minute later. The result of this process was not suitable for GUM because it caused segregation; that is, separation of coarse and fine aggregates that make up GUM.

On the other hand, when comparing the amount of material that remained at the beginning of the pipe for each amplitude, it was possible to conclude that while frequency was increased keeping constant amplitude, the remaining materials at the beginning of the pipe decreased. But, even though frequency and amplitude were increased in the equipment, productivity was very low.

The operation of the equipment was not proper for: S = 20°, A = 3 cm and F = 170 RPM (Figure 23). Also the operation of equipment was not proper for: S = 20°, A = 5 cm and F = 160 RPM (Figure 23). Additionally, the operation of the equipment was not suitable for: S = 30°, A = 5 cm and F = 150 RPM (Figure 25). In the case of S = 25° the equipment faced the same problem when set S = 20°. Those previous problems mean that it was impossible to set those frequencies in the equipment with those amplitudes and slopes of the pipe, carrying out the experiment with water content of 3% in GUM. That is why, with S = 20° and S = 25° the highest frequency was set at 150 RPM, but in the case of S = 30° the highest frequency was set at 140 RPM.

Therefore, it was necessary to increase the productivity of the equipment in the laboratory, to guarantee good productivity of the full-scale equipment in the asphalt plant. There were two options to do it; the first one was to increase as much as possible the slope of the pipe, and the second one was to increase as much as possible the frequency of the equipment.

To increase the slope of the pipe it was not appropriate, because it should be less than 35°, to increase, as much as possible, the processing time of the GUM inside the equipment. Then, taking into consideration this point of view, it was not proper to consider a slope of the pipe higher than 30°.

In the case of frequency, it was also difficult to increase it as much as possible, because the operation of the equipment was not proper with some sets of characteristics for the experiment as was explained before. Therefore, it was difficult to increase, the frequency in the equipment with amplitudes of 3 and 5 cm.

Analyzing the operation of the apparatus in the laboratory with amplitude of 1 cm, it was possible to conclude that there was not restriction to increase its frequency. Even if the frequency was increased, with any slope of the pipe, the operation of the equipment was good. Therefore, with an amplitude of 1 cm, it was possible to use both techniques mentioned above to increase productivity: to increase frequency and to increase slope of the pipe.

Many tests were made in the laboratory to select the proper frequencies to carry out the movement analysis of GUM with 3% of water content. After analyzing the results, frequencies of 220 RPM, 240 RPM, 260 RPM and 280 RPM were chosen.

Figure 26, 27, 28 and 29 show graphically the amount of materials (productivity) with water content of 3% that the equipment was able to process in one hour, with slope of the pipe of 15°, 20°, 25° and 30° respectively. In every figure the frequency was changed.

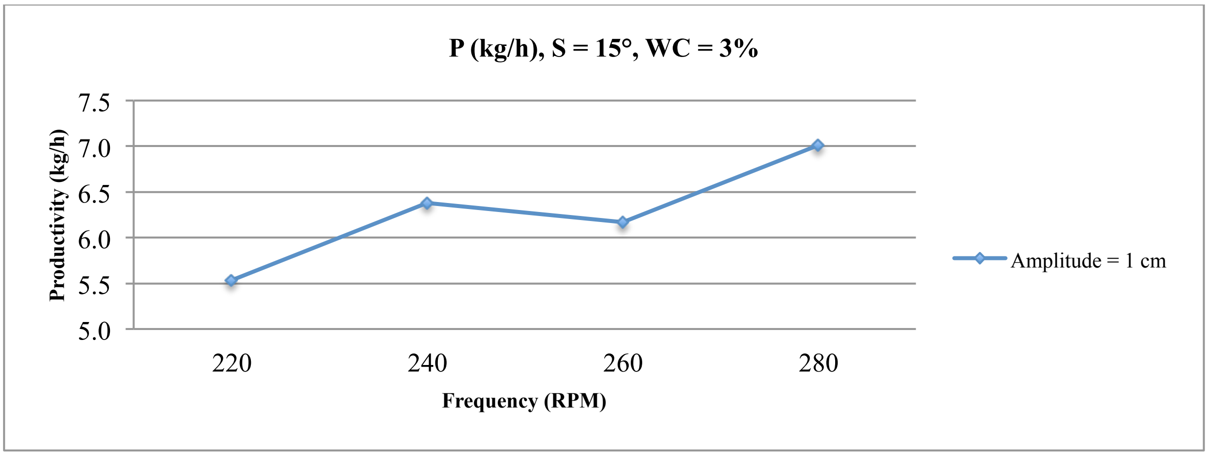

Fig. 26 Relationship between Productivity and Frequency (S=15°, WC=3%)

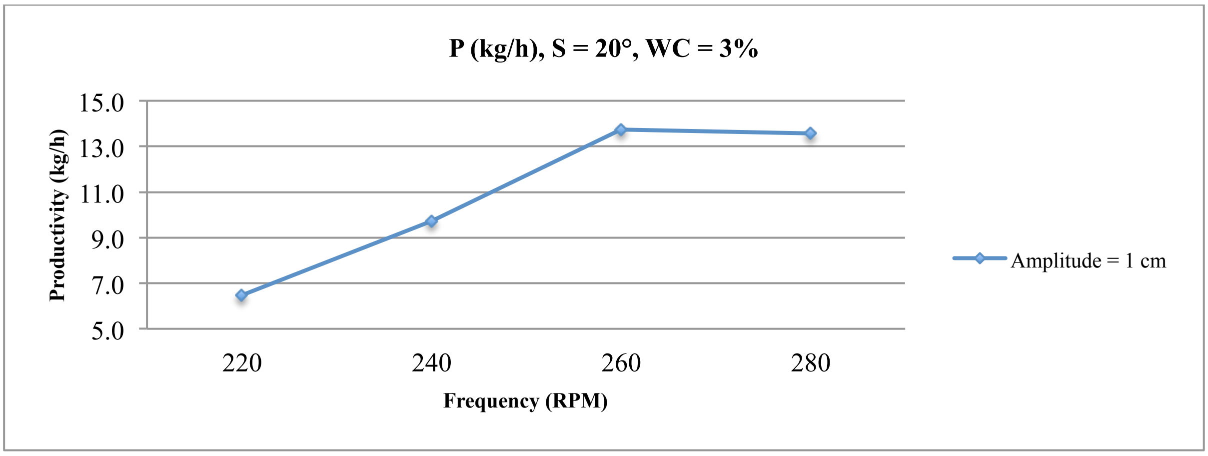

Fig. 27 Relationship between Productivity and Frequency (S=20°, WC=3%)

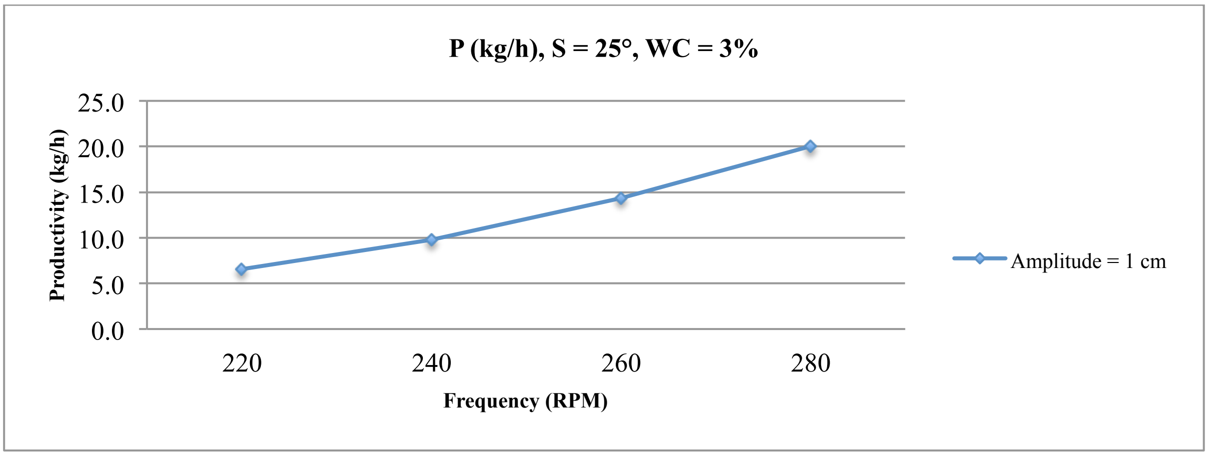

Fig. 28 Relationship between Productivity and Frequency (S=25°, WC=3%)

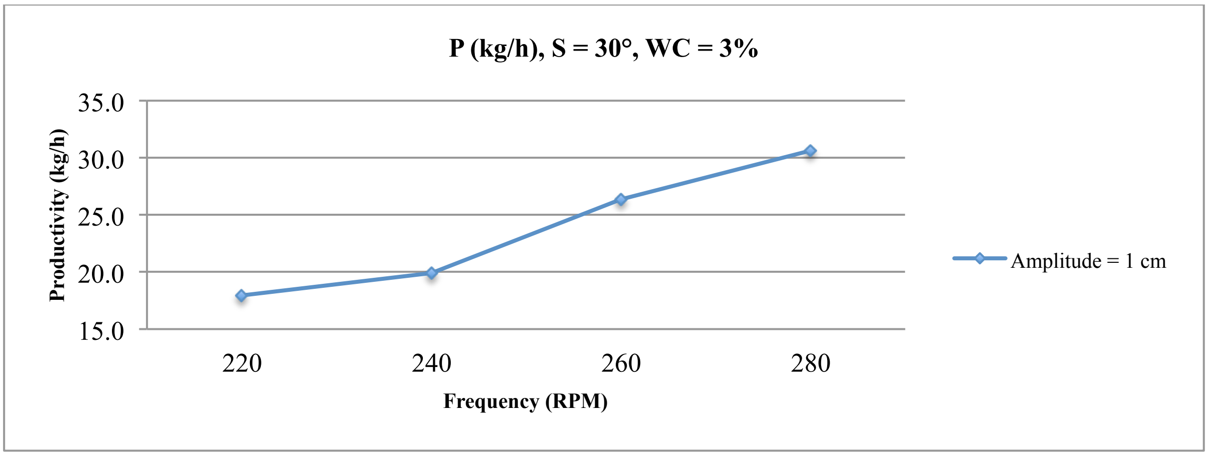

Fig. 29 Relationship between Productivity and Frequency (S=30°, WC=3%)

Figure 30 also shows the productivity of the apparatus, but this time from a different point of view, because in this figure the frequency and the slope of the pipe were changed.

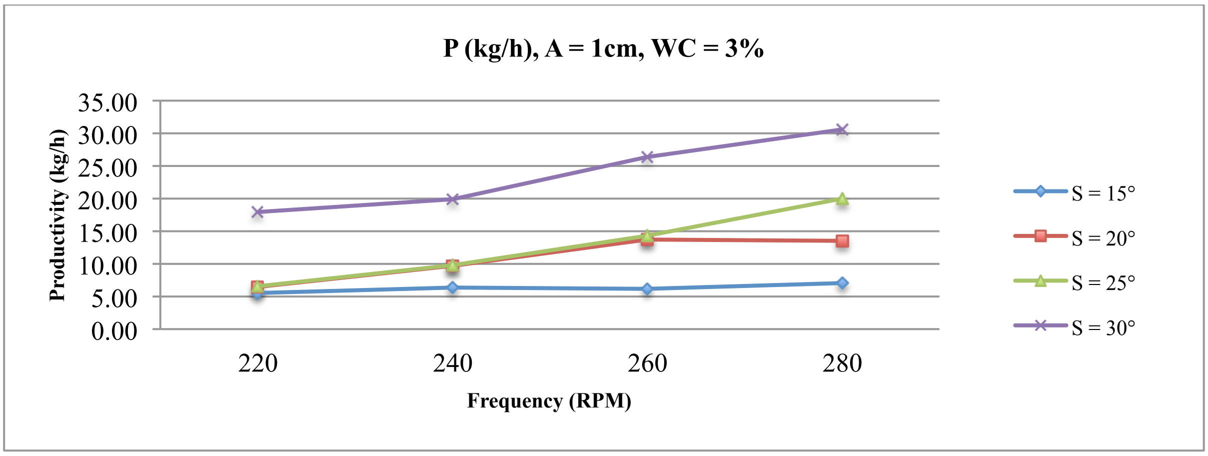

Fig. 30 Relationship between Productivity and Frequency (A=1cm, WC=3%)

The experiments were carried out by changing frequency and slope of the pipe, with the purpose of checking the behavior of the GUM. The experimental results from Figure 26, 27, 28, 29 and 30 demonstrate that while frequency was increased the amount of material that the equipment was able to process in one hour increased.

Also, when comparing the amount of material that the equipment was able to process in one hour for each slope of the pipe, it was possible to conclude that while the slope of the pipe was increased, productivity also increased regardless the frequency.

On the other hand, if the productivity of the equipment in the laboratory was more than 30 kg/h, the processing time of the GUM inside the apparatus was a little short. In addition, it was possible to increase even more the equipment productivity when the slope of the pipe was changed from 25° to 30° than when it was changed from 15° to 20° and from 20° to 25°

Higher productivity in the equipment was obtained in every slope of the pipe with frequencies of 240 RPM, 260 RPM, 280 RPM. But the processing time of GUM inside the apparatus with productivity higher than 30 kg/h, was a little short. Therefore, it was decided to start the experiments to measure soil content in the processed asphalt aggregate with the frequencies mentioned above and slope of the pipe equal to 25°. Figure 31 shows the set of characteristics that will be established in the equipment to start the experiments with water content of 3% in the GUM.

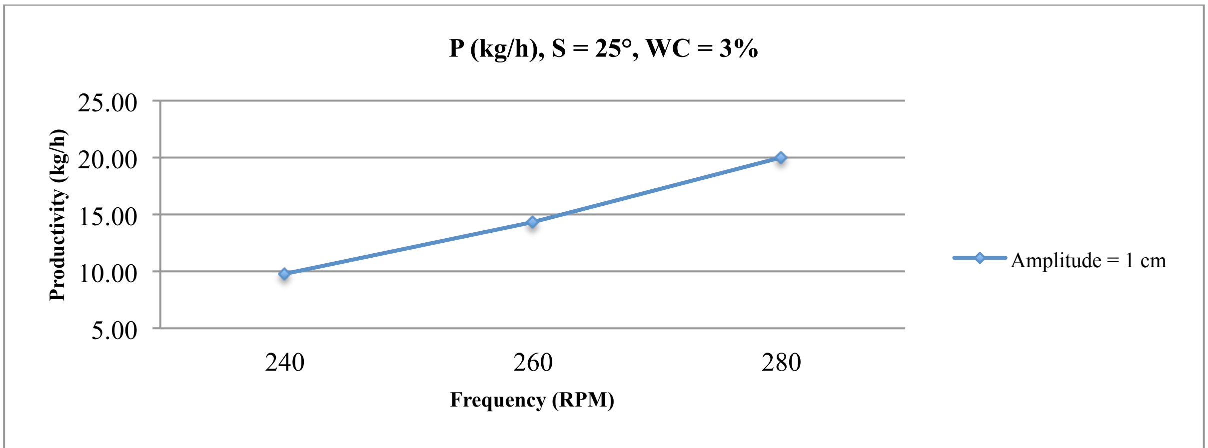

Fig. 31 Relationship between Productivity and Frequency (S=25°, WC=3%)

2.5.3 Experimental results (WC = 5%)

GUM with 5% of water content caused the same problem of low productivity in the equipment. Therefore, high frequencies of 220 RPM, 240 RPM, 260 RPM, 280 RPM and small amplitude of 1 cm are the characteristics chosen to carry out the movement analysis. Then, the method to treat the material to process with 5% of water content will be the same used to process the GUM with 3% of water content.

Figure 32, 33, 34 and 35 show graphically the amount of materials (productivity) with 5% of water content that the equipment was able to process in one hour, with slope of the pipe of 15°, 20°, 25° and 30° respectively. In every figure the frequency was changed.

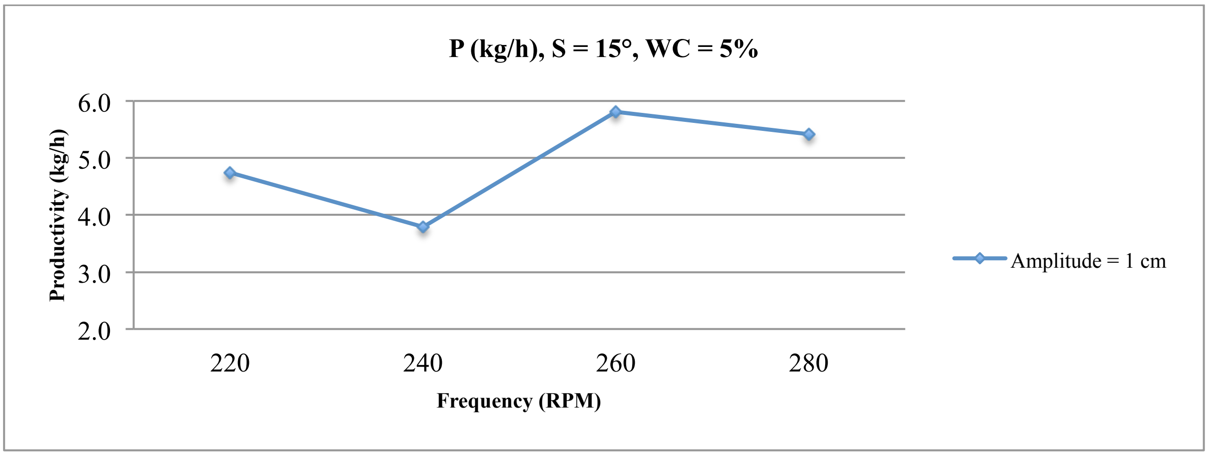

Fig. 32 Relationship between Productivity and Frequency (S=15°, WC=5%)

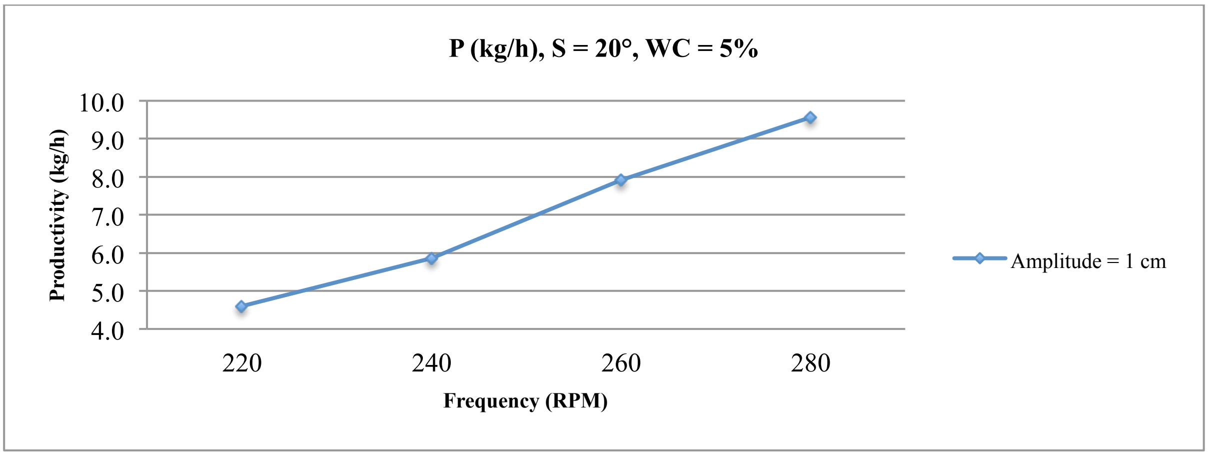

Fig. 33 Relationship between Productivity and Frequency (S=20°, WC=5%)

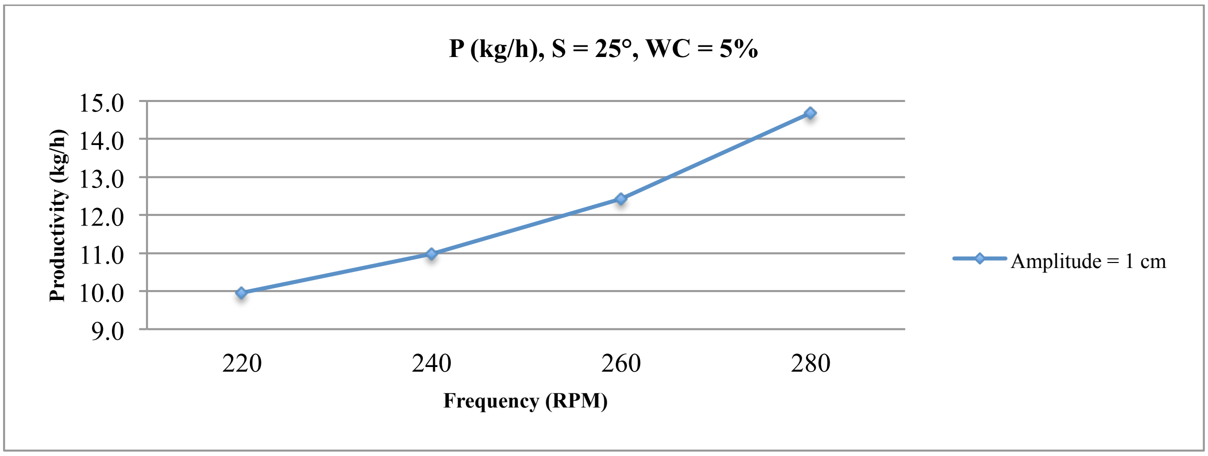

Fig. 34 Relationship between Productivity and Frequency (S=25°, WC=5%)

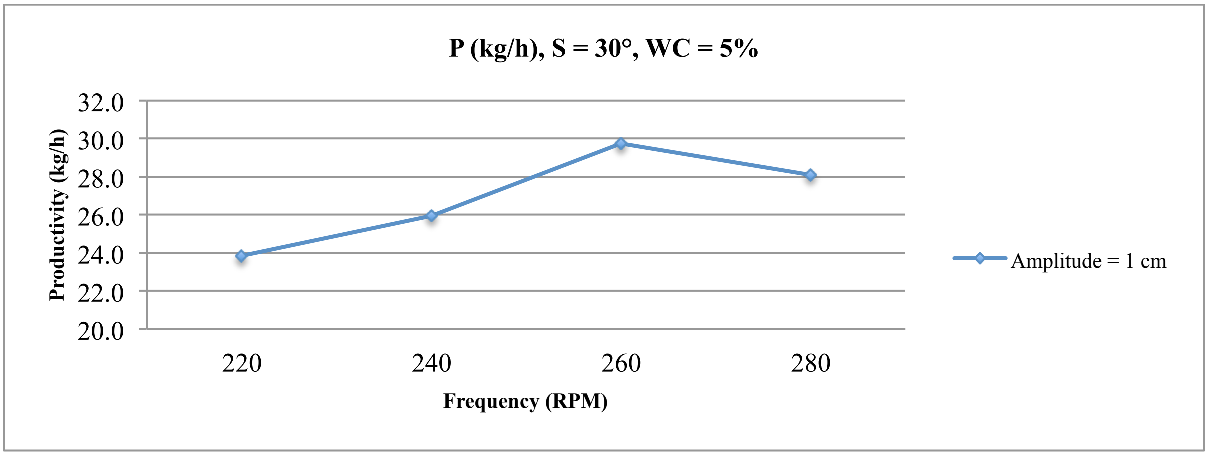

Fig. 35 Relationship between Productivity and Frequency (S=30°, WC=5%)

Figure 36 also show the productivity of the apparatus, but this time from a different point of view, because in this figure the frequency and the slope of the pipe were changed.

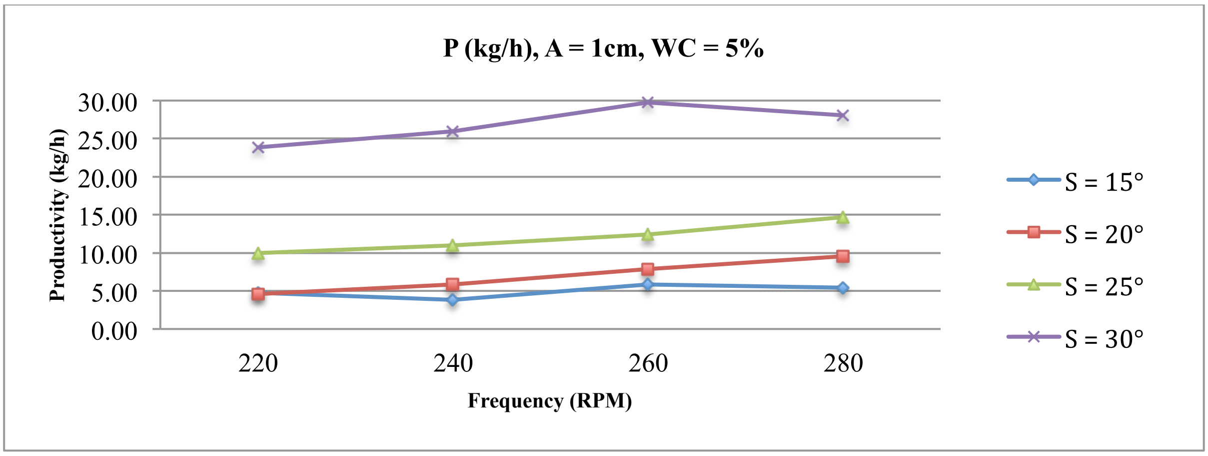

Fig. 36 Relationship between Productivity and Frequency (A=1cm, WC=5%)

The experiments were carried out by changing frequency and slope of the pipe, with the goal to check the behavior of GUM. The experimental results from Figure 32, 33, 34, 35 and 36 demonstrate that while frequency was increased the amount of material that the equipment was able to process in one hour generally increased.

Besides, if high frequency with small amplitude of 1 cm was established in the equipment, it was possible to reduce to a minimal amount the material remaining at the beginning of the pipe. Also, when comparing the amount of material that the equipment was able to process in one hour for each slope of the pipe, it was possible to conclude that while the slope of the pipe increases, productivity also increases regardless the frequency.

On the other hand, if the pipe slope was set at 30° with amplitude of 1 cm in the equipment and the GUM had a 5% of water content, little segregation was produced. Additionally, it was possible to increase even more the equipment productivity when the slope of the pipe was changed from 25° to 30° than when it was changed from 15° to 20° and from 20° to 25°.

In most cases higher productivity of the equipment was obtained in every slope of the pipe with frequencies of 240 RPM, 260 RPM, and 280 RPM. If the pipe slope was set at 30° with amplitude of 1 cm in the equipment and the GUM had a 5% of water content, little segregation was produced. Therefore, it was decided to start the experiments to measure soil content in the material to process with the frequencies mentioned above and slope of the pipe at 25°. Figure 37 shows the set of characteristics that will be established in the equipment to start the experiments with water content of 5% in the GUM.

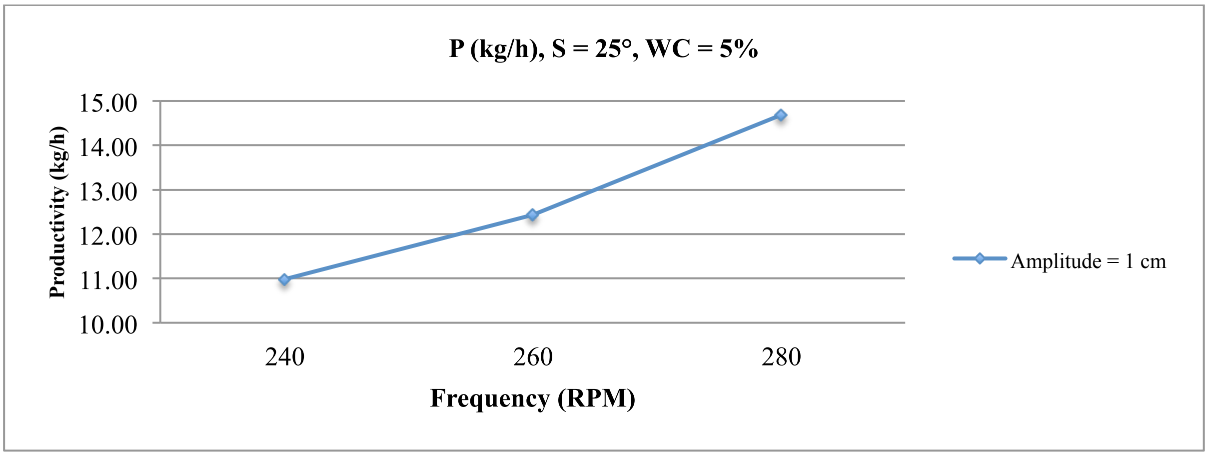

Fig. 37 Relationship between Productivity and Frequency (S=25°, WC=5%)

2.6 Summary of Chapter 2

Taking into consideration the experimental results and analysis described above, the following partial conclusions can be drawn from the experimental study on movement of GUM:

- Movement properties of GUM with 1% and 3% of water content are different, because the processing methods to treat them inside the apparatus are different. The same phenomenon occurs with 1% and 5 % of water content.
- Movement properties of GUM with 3% and 5% of water content are similar, because the processing methods to treat them inside the apparatus are the same.
- If high frequency with small amplitude of 1 cm is established in the equipment, it is possible to reduce to a minimal amount the material remaining at the beginning of the pipe when the water content in the GUM is high.

- It is recommended do not use pipe inclination angle lower than 15°, in the case of high water content (3% and 5%) in GUM, when use amplitude equal 1cm, because the productivity of the equipment is very low.

CHAPTER 3 EXPERIMENTAL STUDY ON REDUCTION OF SOIL CONTENT IN GRIZZLY UNDER MATERIALS

CHAPTER 3 EXPERIMENTAL STUDY ON REDUCTION OF SOIL CONTENT IN GRIZZLY UNDER MATERIALS

3.1 Experimental apparatus

The experimental study on reduction of soil content in GUM after establishing the new proposed set of characteristics in the equipment was carried out in Takahashi Laboratory. The experimental apparatus used in this study was the same that was used in Chapter 2: Experimental study on Movement of Grizzly under Materials.

3.2 Experimental procedure

The experimental study on reduction of soil content in GUM was carried out as follows:

1. To prepare a large sample of GUM (12 kgs) taking into consideration the Japanese Industrial Standard (JIS) A 1158, 2014 [30].
2. The large sample of GUM was divided into 4 small samples.
3. One of those four samples was considered the control sample to measure the initial soil content of non-processed GUM in the equipment. Soil content in the control sample was measured taking into consideration the Japanese Industrial Standard (JIS) A 1103, 2014 [31]
4. A certain amount of water was poured into the other three samples of GUM, to achieve the decided water content (1%, 3%, 5%) depending on the test.
5. The slope of the pipe was set at an angle lower than 35°, taking into consideration the slope of the pipes obtained in the Chapter 2 Experimental study on Movement of Grizzly under Materials.
6. To start the large compressor of the equipment.
7. To start the suction machine of the equipment.
8. To start the vibration device of the equipment, taking into consideration the frequencies and the amplitudes obtained in the Chapter 2 Experimental study on Movement of Grizzly under Materials.
9. The three other samples were fed twice into the equipment to simulate two suction places in the apparatus, taking into consideration the water content decided in the Chapter 2 Experimental study on Movement of Grizzly under Materials.
10. Soil content in every processed recycled aggregate in the equipment was measured taking into consideration the Japanese Industrial Standard (JIS) A 1103, 2014 [31].

11. The final soil content in the processed recycled aggregate was calculated with the average of the 3 soil contents obtained in step 10.
12. To establish a comparison between the initial soil content and the final soil content in the experimental materials to check the capacity of the equipment to reduce the soil content in the GUM as much as possible.
13. To repeat from step 1 to step 12 until every water content, frequency, amplitude and slope of the pipe obtained in the Chapter 2 Experimental study on Movement of Grizzly Under Materials is tested.

3.3 Experimental specimens used in this study

To carry out the experimental study on reduction of soil content in GUM in Takahashi Laboratory were used the recycled asphalt materials form Sendai Asphalt Plant of Maeda Road Construction Co., Ltd; and most of them did not match the required value for Amount of soils shown in Table 1 [8]. The materials used in this study were the same materials used in Chapter 2: Experimental study on Movement of Grizzly under Materials.

3.4 Results and discussion

3.4.1 Parameters to check in the screenless equipment

The study on reduction of soil content in the GUM has several parameters to take into consideration, at construction site. Therefore, it is needed to control those parameters to check the equipment performance in the laboratory. In this study, rate of suction, recovery and attached materials on the pipe inner surface were measured to investigate the performance of the equipment.

Rate of suction: It is the capacity that the screenless separation equipment has to reduce the initial soil content in GUM, that is, the difference in percent between the initial soil content before the process and final soil content after the process inside the apparatus. This parameter will be measured in %.

Equation 1 shows the formula used for determining the rate of suction values.

$Rs = Isc - Fsc$ (1)

where:

Rs = rate of suction (%); Isc = initial soil content in GUM (%); Fsc = final soil content in GUM (%)

Rate of suction of the screenless separation equipment is the most important property to check because the main objective of this equipment is to reduce the soil content in the GUM as much as possible. Therefore, while the rate of suction of the equipment increases, the apparatus will be able to reduce even more the initial soil content in GUM.

Recovery: It is the capacity that the screenless separation equipment has to obtain at the end of the process, the largest possible amount of recycled asphalt aggregates. That is, the percentage that represents the mass of the processed materials that were obtained after the process in the equipment with respect to the initial total mass of GUM that was fed into the apparatus. This parameters will be measured in %.

Using the described procedure in the section “3.2 Experimental procedure” to determine the rate of suction, it is possible to determine the recovery at the same time. In the process of adding each sample of GUM with the decided water content into the equipment, from the initial total mass of GUM to feed into the apparatus there is a certain amount of material that it will remain attached on the pipe inner surface, a certain amount of material that it will be sucked by the suction machine and a certain amount of processed aggregate that it will be obtained at the end of the process in the equipment. Therefore, the mass of processed aggregate will be lower than the initial total mass of GUM that was fed into the equipment. Hence, it is important to know which percentage of the initial total mass of GUM is obtained at the end of the process in the apparatus, this fact decides the recycled aggregate production at construction site. The previous mentioned percentage constitutes the recovery of GUM, that the equipment is able to obtain at the end of the process. Equation 2 shows the formula used for determining the recovery values.

$$Rec = \left(\frac{Pm}{Itm}\right) * 100 \quad (2)$$

where:

Rec = recovery (%); Pm = mass of processed GUM obtained after the process in the equipment (gr); Itm = initial total mass of GUM that was fed into the equipment (gr).

Recovery is also very important. This property shows the capacity of the equipment to obtain at the end of the process, the higher amount of recycled aggregate respect to the initial total mass of GUM that was fed into the apparatus. This parameter has a great influence in the aggregate production at the construction site. Hence, while the recovery of the equipment increases, the apparatus will be able to obtain more recycled asphalt aggregates at the end of the process, this fact is very important for recycled aggregate production at construction site.

Attached material on the pipe inner surface: This parameter shows the percentage that represents the mass of the materials that remain attached on the pipe inner surface respect to the initial total mass of GUM that was fed into the equipment. This parameter will be measured in %.

As it was explained before, in the process of adding each sample of GUM with the decided water content into the equipment, from the initial total mass of GUM to feed into the apparatus, there is a certain amount of material that it will remain attached on the pipe inner surface. Using the same described procedure, in the section “3.2 Experimental procedure”, to determine the rate of suction, it is possible to determine the attached material on the pipe inner surface at the same time. It is very important to check this phenomenon in detail, because if the amount of material that remain attached on the pipe inner surface increases, clogging of the pipe can occurs very soon. This fact will affect the production of recycled aggregate at construction site. Equation 3 shows the formula used for determining the attached material on the pipe inner surface values.

$$Att = \left(\frac{[Itm-(Pm+Sm)]}{Itm}\right) * 100 \quad (3)$$

where:

Att = attached material on the pipe inner surface (%); Itm = initial total mass of GUM that was fed into the equipment (gr); Pm = mass of processed GUM obtained after the process in the equipment (gr); Sm = mass of material sucked by the suction machine

Besides, attached materials on the pipe inner surface are very important too. If the volume of attached materials inside the equipment is large, clogging of the pipe will occur very soon. This fact is bad for the equipment performance and for recycled aggregate production at construction site. Therefore, it is necessary to reduce the attached materials inside the pipe of the apparatus as much as possible.

From the point of view of the researcher, the explained parameters are very important for the success of reduction activity of soil content in the GUM lower than 5 percent. For that reason, those parameters will be checked in the laboratory, controling the experimental conditions, to infer the performance of full-scale equipment at construction site.

3.4.2 Validation experiments. Usefulness of newly proposed screenless equipment.

Validation experiments were conducted in an attempt to confirm the usefulness of newly proposed screenless equipment with a vibration device. The pipe inclination angle was set at 40°, 25°, 15°. In case of 40°, vibration was not added. That is, this condition corresponds to the previous equipment. In the case of 25° and 15°, the frequency of vibration was set to 260RPM and the amplitude of vibration was set to 1cm. Water content was adjusted to be 5%, to carry out those experiments.

Figure 38 shows the percent of soil contained in GUM before and after the process inside the equipment, the figure in question is divided in two sections by a black dushed line, section at the left side shows the performance related with previous equipment, section at the right side shows the performance related with the newly proposed one.

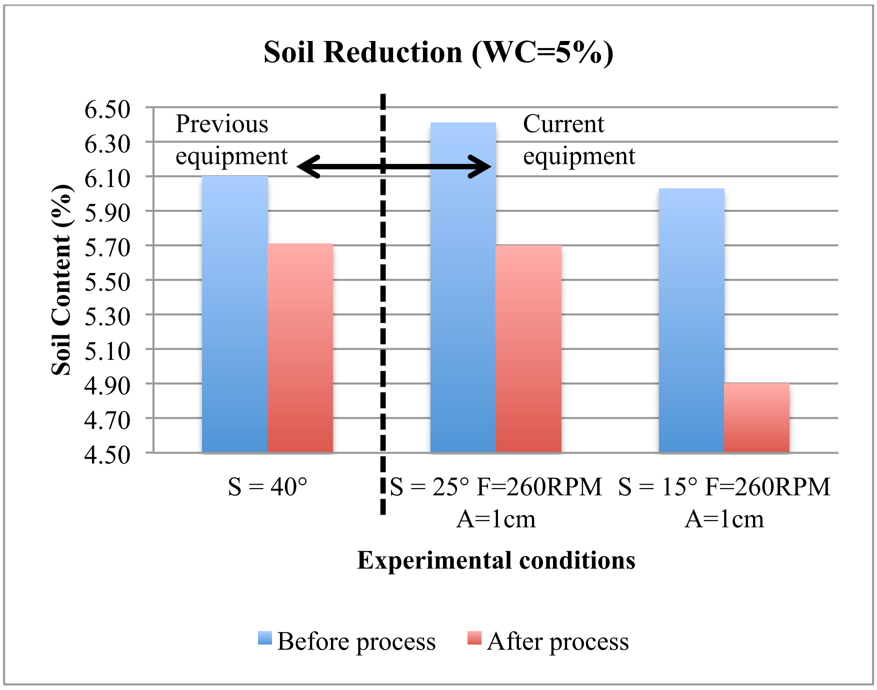

Fig. 38 Soil content before and after the process (WC=5%)

Figure 39 shows the rate of suction that were achieved by previous and newly proposed equipment, the figure in question is divided in two sections by a black dushed line, section at the left side shows the performance related with previous equipment, section at the right side shows the performance related with the newly proposed one.

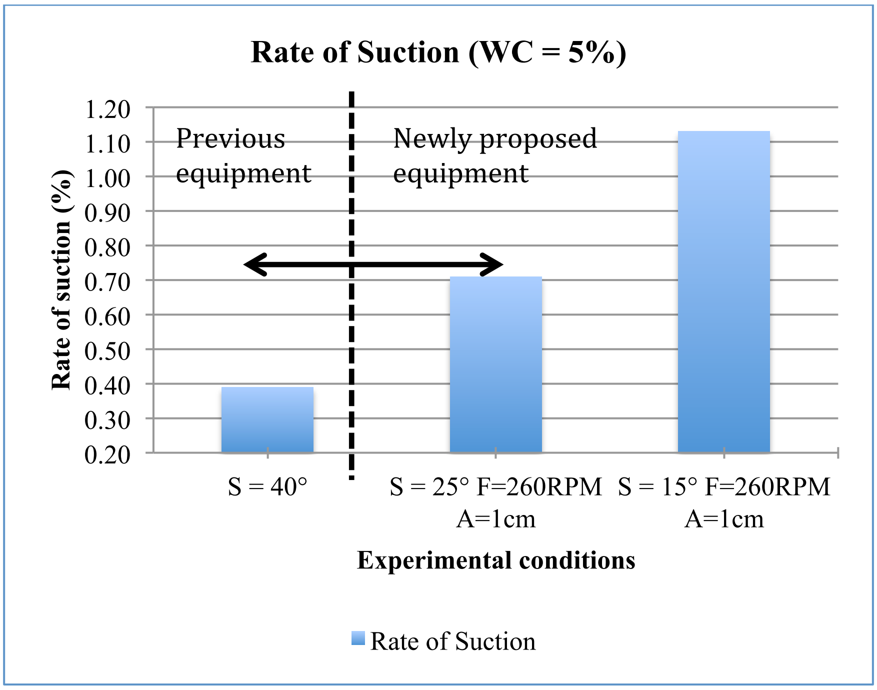

Fig. 39 Rate of suction (WC=5%)

Fig. 39 Rate of suction (WC=5%)

As shown in Figure 38 and 39, the effect of adding vibration is significant and rate of suction by the newly proposed equipment in this study was much lager than that by previous one. That is, the usefulness of the new equipment was confirmed.

3.4.3 Experimental results (WC = 5%, A = 1cm with S = 25° and S = 15°)

The first experimental study on reduction of soil content in GUM in Takahashi Laboratory to measure the performance of the newly proposed screenless separation equipment was carried out with 5% of water content in the material to process and 25° of slope of the pipe and then this latter parameter was changed to 15°.

Figure 40 shows graphically the soil content in the GUM before and after the process inside the screenless separation equipment. Those values correspond to the following set of characteristics: WC=5%, A=1cm with S=25° and S=15°.

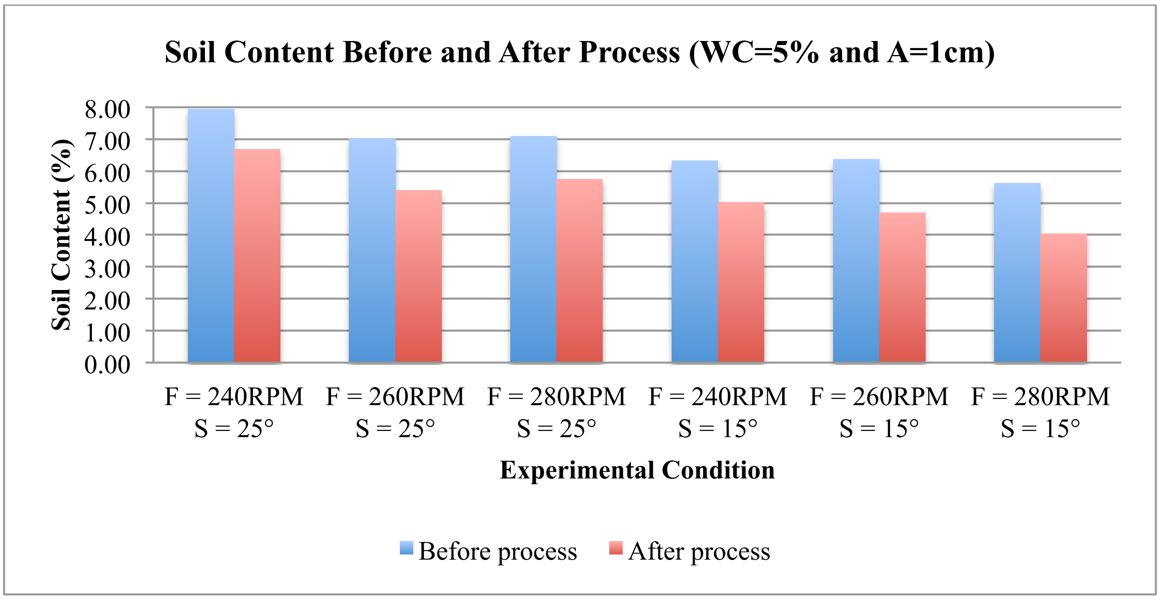

Fig. 40 Soil content before and after the process (WC=5%, A=1cm with S=25 and S=15)

From the experimental results shown in Figures 40, it was possible to conclude that the equipment was able to reduce the soil content in GUM and the soil contents in the GUM before the process inside the equipment, did not meet the required value (soil content less than 5%). However, even though the soil content was reduced, the soil content in GUM after the process did not satisfy the required value under the experimental conditions of S=25° regardless the frequency. In the case of S=15°, the soil content in GUM after the process in the equipment was lower than 5, regardless the frequency, except for F=240RPM.

Figure 41 shows graphically the rate of suction of the screenless separation equipment when dealing with the soil content in the GUM. Those rate of suction values are related to the following group of characteristics: WC=5%, A=1cm with S=25° and S=15°.

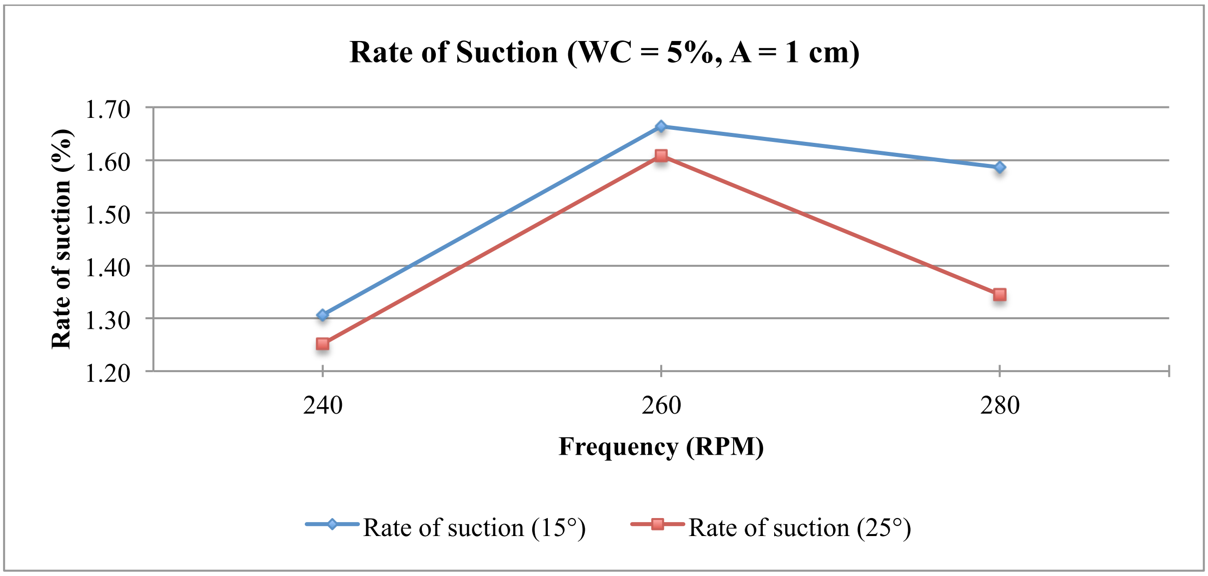

Fig. 41 Relationship between Rate of Suction and Frequency (WC=5%, A=1cm with S=15 and S=25)

The experimental results shown in Figure 41 demonstrate that the highest performance of the equipment (rate of suction) was obtained with frequency of 260 RPM and the lowest performance of the equipment was obtained with frequency of 240 RPM regardless the slope of the pipe. But the rate of suction of the equipment with slope of the pipe equal to 15° was higher than the equipment performance with slope of the pipe equal to 25°, regardless the frequency.

There was an interesting phenomenon in the behavior of this parameter (rate of suction): because from 240 RPM to 260 RPM rate of suction increased but from 260 RPM to 280 RPM this parameters decreased. This phenomenon happened because while high frequency was increased with small amplitude, the equipment was able to reduce more the soil content in GUM, since those characteristics helped the swirl air flow to separate soils particles from the surface of the coarse aggregates that make up the asphalt material to process. But at the same time, while high frequency was increased with small amplitude, the processing time inside the equipment decreased and the equipment performance decreased too. It means, there is a convenient processing time for GUM inside the apparatus for each pipe inclination angle. Therefore, that is why the rate of suction of the equipment from 240 RPM to 260 RPM increased but from 260 RPM to 280 RPM it decreased.

Figure 42 shows graphically the recovery of the screenless separation equipment when dealing with the GUM. Those recovery values are associated to the following group of characteristics: WC=5%, A=1cm with S=25° and S=15°.

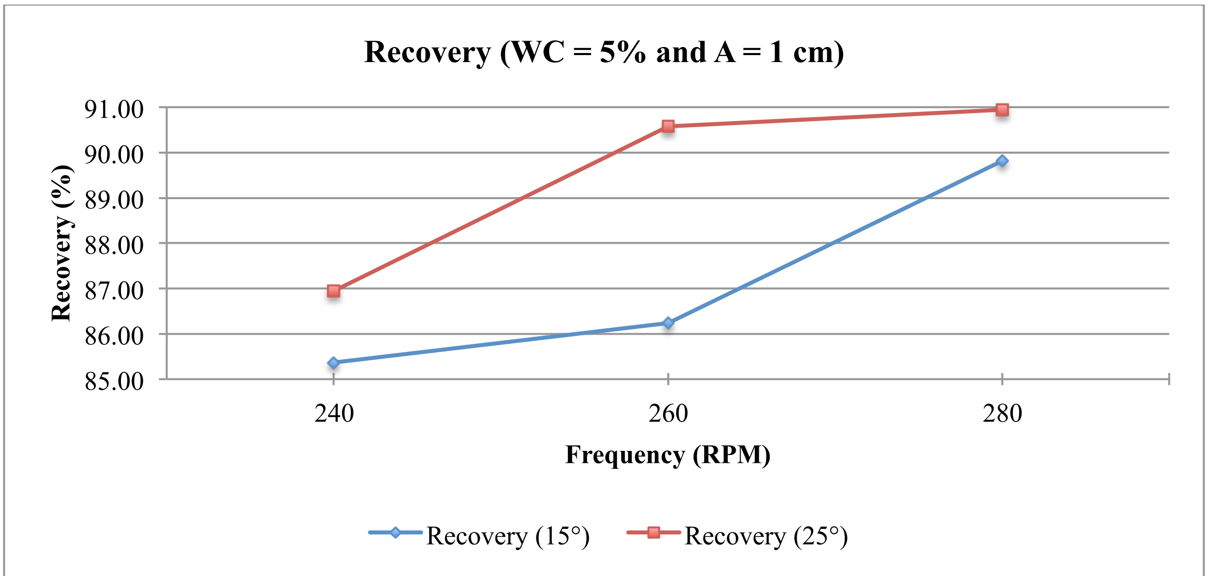

Fig. 42 Relationship between Recovery and Frequency (WC=5%, A=1cm with S=25 and S=15)

When the experimental results from Figure 42 were analyzed, it was possible to conclude that while the frequency was increased the recovery of the equipment increased too, regardless the slope of the pipe. But the recovery of the equipment with slope of the pipe equal to 25° was higher than the apparatus performance, in the mentioned parameter, with slope of the pipe equal to 15°, regardless the frequency. The highest recovery of the equipment was obtained with frequency of 280 RPM and the lowest recovery of the equipment was obtained with frequency of 240 RPM, regardless the slope of the pipe.

Figure 43 shows graphically the attached materials on the inner surface of the pipe of the screenless separation equipment as a result of water content. Those attached material values correspond to the following set of characteristics: WC=5%, A=1cm with S=25° and S=15°.

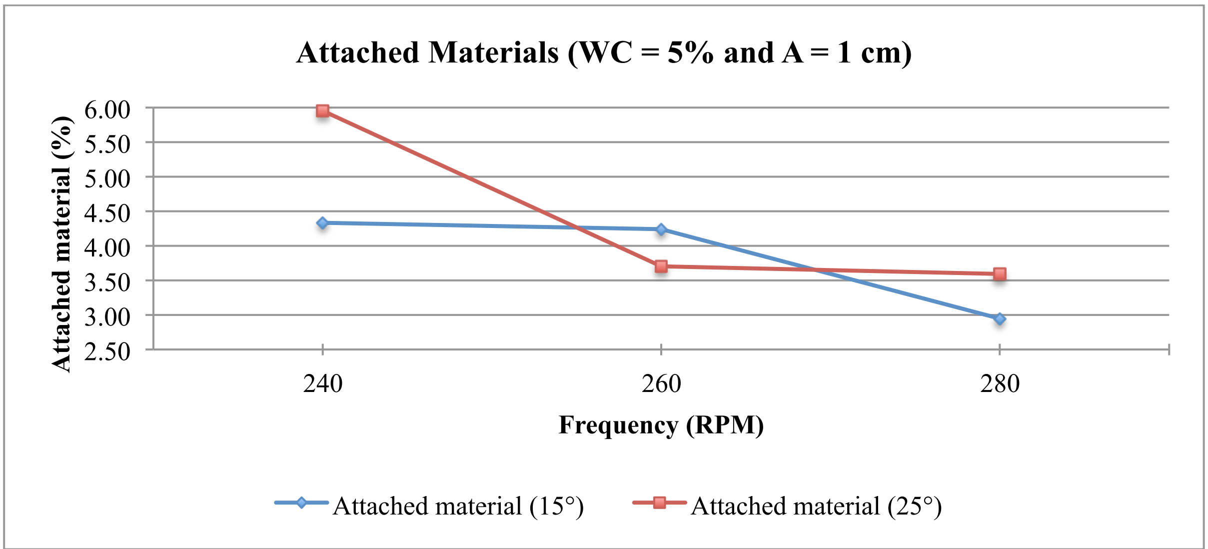

Fig. 43 Relationship between Attached Materials and Frequency (WC=5%, A=1cm with S=25 and S=15)

The experimental results from Figure 43 demonstrate that, while frequency was increased, the remaining material inside the pipe decreased, regardless the slope of the pipe. But the amount of attached materials inside the pipe of the equipment with slope of the pipe equal to 15° was lower than the mentioned parameter with slope of the pipe of 25°, regardless the frequency, except with F = 260 RPM. The highest amount of attached material inside the pipe was obtained with frequency of 240 RPM and the lowest amount of attached material inside the pipe was obtained with frequency of 280 RPM.

3.4.4 Experimental results (WC = 3%, A = 1cm with S = 25°and S = 15°)

The second experimental study on reduction of soil content in GUM in Takahashi Laboratory to measure the performance of the newly proposed screenless separation equipment was carried out with 3% of water content in the material to process and 25° of slope of the pipe and then this latter parameter was changed to 15°.

Figure 44 shows graphically the soil content in the GUM before and after the process inside the screenless separation equipment. Those values correspond to the following set of characteristics: WC=3%, A=1cm with S=25° and S=15°.

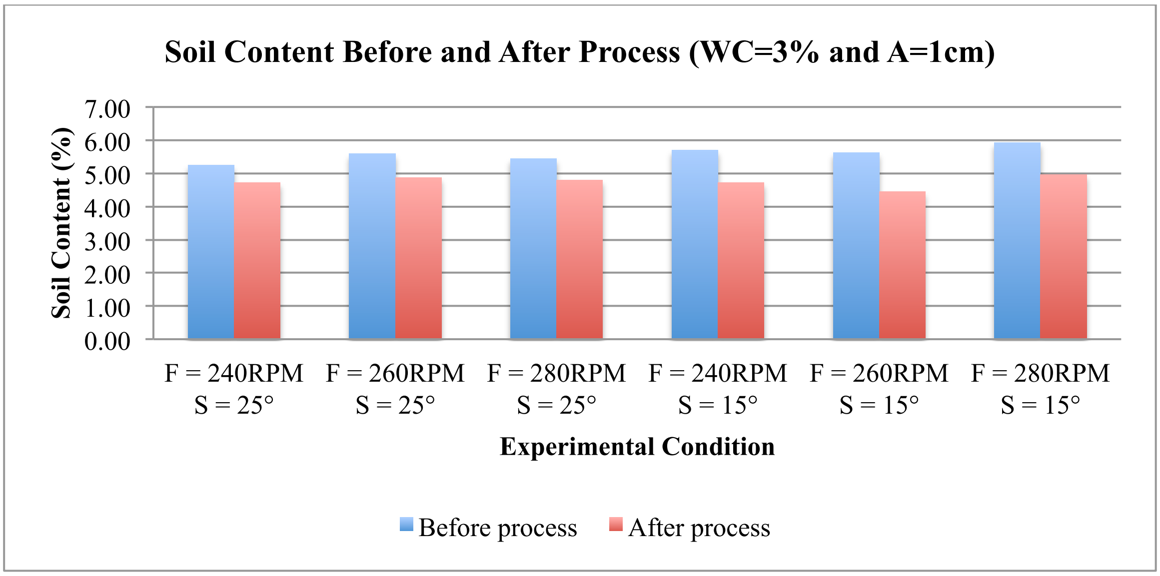

Fig. 44 Soil content before and after the process (WC=3%, A=1cm with S=25 and S=15)

From the experimental results shown in Figures 44, it was possible to conclude that the equipment was able to reduce the soil content in GUM and the soil contents in the GUM before the process inside the equipment, did not meet the required value (soil content less than 5%). The soil content in GUM after the process satisfy the required value all the time, regardless the frequency and the slope of the pipe.

Figure 45 shows graphically the rate of suction of the screenless separation equipment when dealing with the soil content in the GUM. Those rate of suction values are related to the following group of characteristics: WC=3%, A=1cm, with S=25° and S=15°.

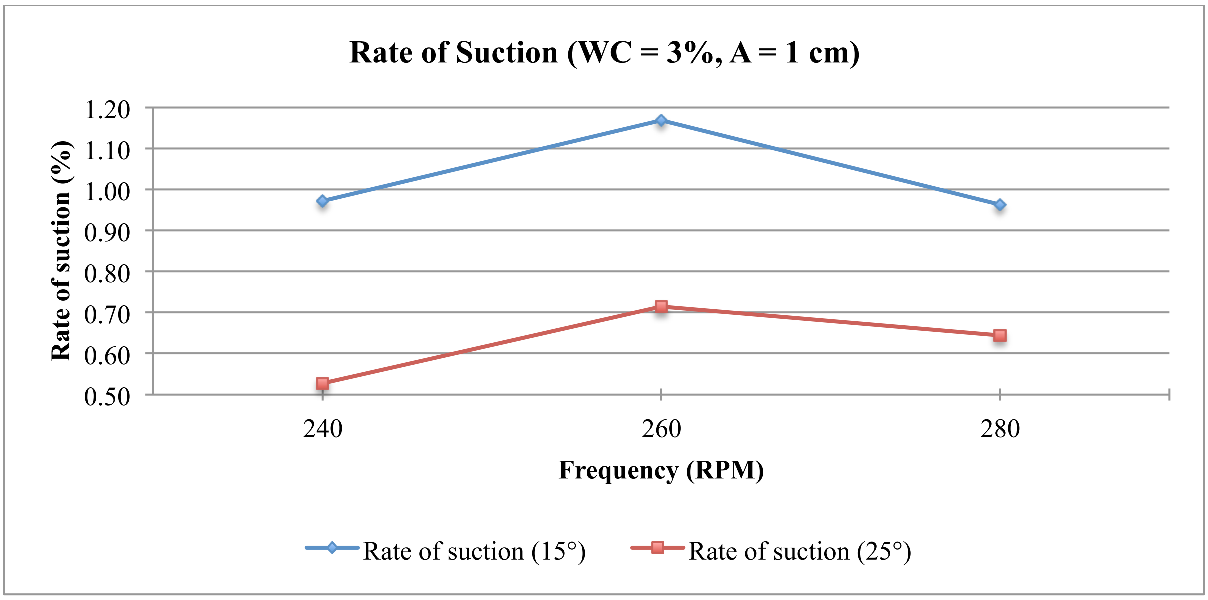

Fig. 45 Relationship between Rate of Suction and Frequency (WC=3%, A=1cm with S=15 and S=25)

The experimental results shown in Figure 45 demonstrate that the highest performance of the equipment (rate of suction) was obtained with frequency of 260 RPM regardless the slope of the pipe and the lowest performance of the equipment was obtained with frequency of 240 RPM in the case of 25° of slope of the pipe and in the case of 15° of pipe slope was obtained with the frequency of 280 RPM. But the rate of suction of the equipment with slope of the pipe of 15° was somewhat higher than the rate of suction with 25°, regardless the frequency.

Figure 46 shows graphically the recovery of the screenless separation equipment when dealing with the GUM. Those recovery values are associated to the following group of characteristics: WC=3%, A=1cm with S=25° and S=15°.

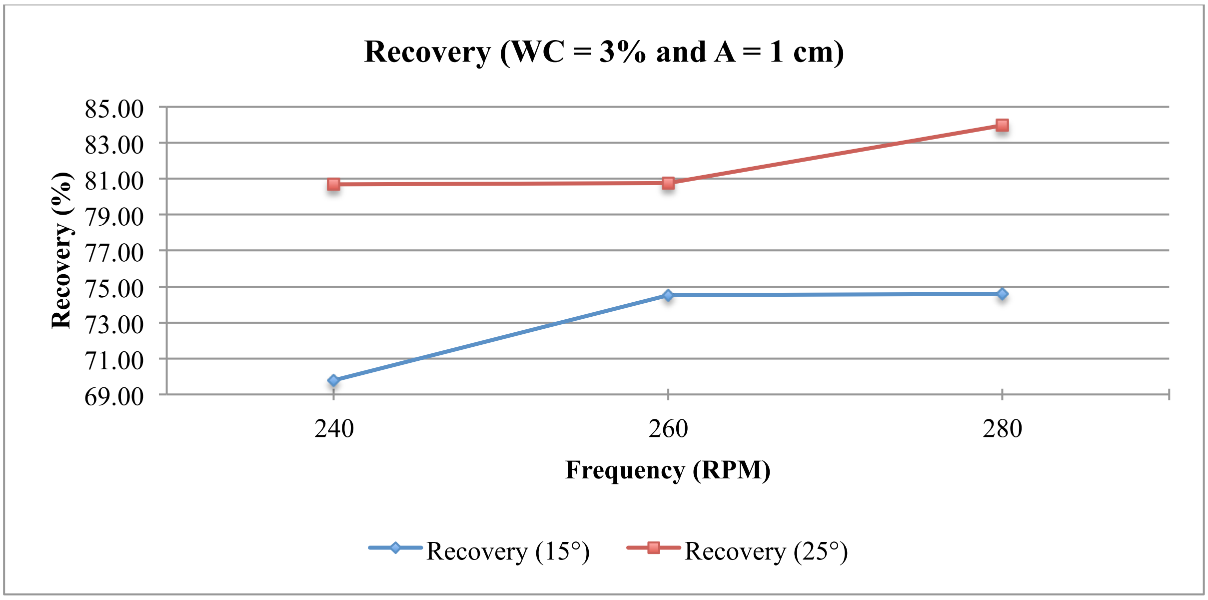

Fig. 46 Relationship between Recovery and Frequency (WC=3%, A=1cm with S=25 and S=15)

When the experimental results from Figure 46 were analyzed, it was possible to conclude that while the frequency was increased the recovery of the equipment increased too, regardless the slope of the pipe. But the recovery of the equipment with slope of the pipe equal to 25° was higher than the apparatus performance, in the mentioned parameter, with slope of the pipe equal to 15°, regardless the frequency. The highest recovery of the equipment was obtained with frequency of 280 RPM and the lowest recovery of the equipment was obtained with frequency of 240 RPM, regardless the slope of the pipe.

Figure 47 shows graphically the attached materials on the inner surface of the pipe of the screenless separation equipment as a result of water content. Those attached material values correspond to the following set of characteristics: WC=3%, A=1cm with S=25° and S=15°.

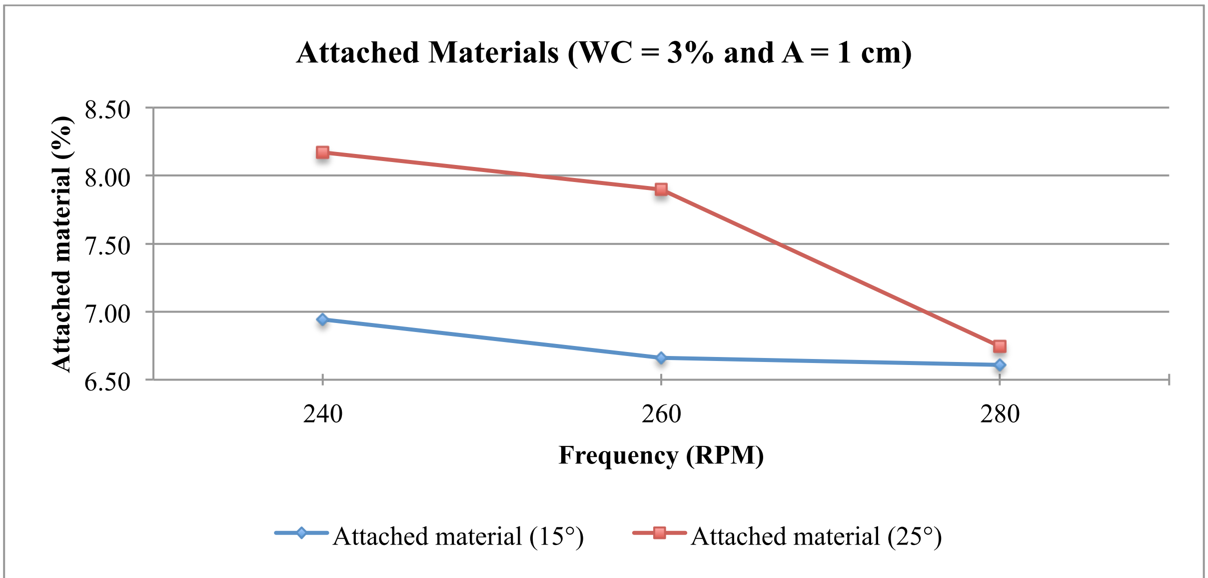

Fig. 47 Relationship between Attached Materials and Frequency (WC=3%, A=1cm with S=25 and S=15)

The experimental results from Figure 47 demonstrate that, while frequency was increased, the remaining material inside the pipe decreased, regardless the slope of the pipe. But the amount of attached materials inside the pipe of the equipment with slope of the pipe equal to 15° was lower than the mentioned parameter with slope of the pipe of 25°, regardless the frequency. The highest amount of attached material inside the pipe was obtained with frequency of 240 RPM and the lowest amount of attached material inside the pipe was obtained with frequency of 280 RPM, regardless the slope of the pipe.

3.4.5 Experimental results (S = 25°, A = 1cm with WC = 5% and WC = 3%)

Figure 48 shows the percent of soil contained in GUM before and after the process inside the equipment, the figure in question shows the equipment performance when dealing with 5% and 3% of water content in GUM, setting in the apparatus the same pipe inclination angle

(25°) and vibration amplitude (1cm). The first 3 blue and orange columns (from left to right) correspond to 5% of water content in GUM, the others columns correspond to 3% of water content in GUM.

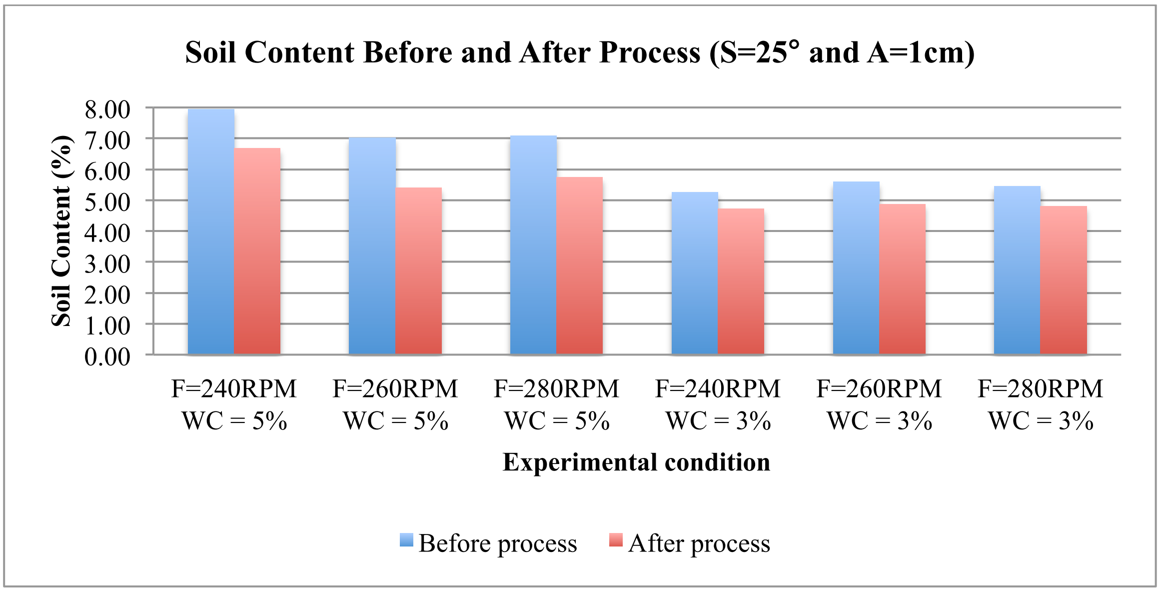

Fig. 48 Soil content before and after process (S=25, A=1cm with WC=5% and WC=3%)

From the experimental results shown in Figures 48, it was possible to conclude that the equipment was able to reduce the soil content in GUM. However, even though the soil content was reduced, the soil content did not satisfy the required value under the experimental conditions of S=25° and A=1cm, when the water content was equal to 5% as shown in Figure 48. On the other hand, when the water content was equal to 3%, although the soil contents in GUM before the process inside the equipment did not satisfy the required value (less than 5%), the soil content in the processed aggregates, after the process inside the equipment was reduced less than 5% and satisfied the required value as shown in Figure 48. Even those experimental results, it is possible to notice that the difference between soil content in GUM, before process and after process inside the equipment is larger in the case of 5% of water content than 3% of water content. This fact means, that the equipment was able to reduce more the initial soil content in GUM when contain 5% of water content than 3% of water content, though the final soil content in GUM when contain 3% of water content was less than 5% (required value).

Figure 49 shows the rate of suction of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 5% and 3% of water content in GUM, setting in the apparatus the same pipe inclination angle (25°) and amplitude of vibration (1cm).

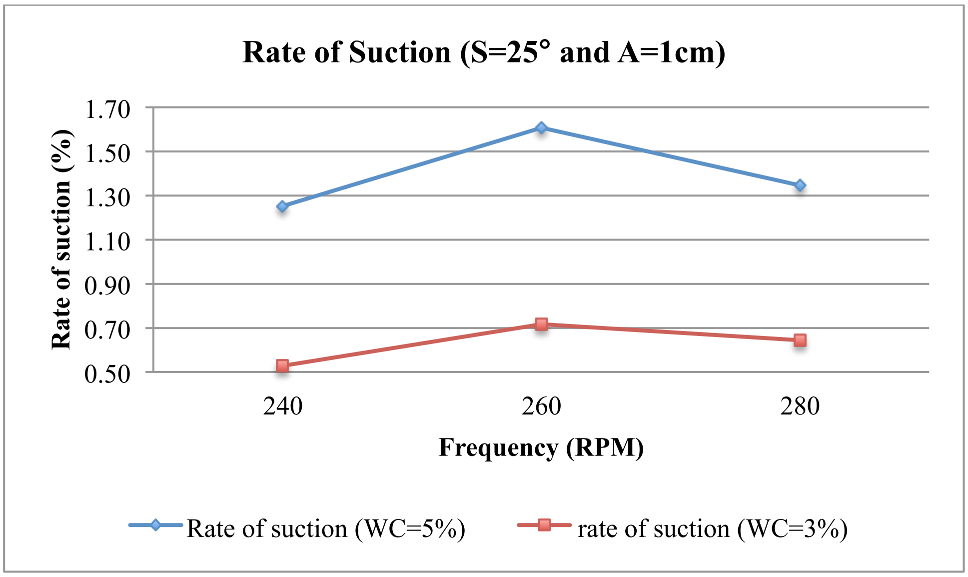

Fig. 49 Relationship between Rate of Suction and Frequency (S=25, A=1cm with WC=5% and WC=3%)

It was confirmed from Figure 49 that the equipment performance when processing GUM with 5% of water content was higher than the equipment performance when processing GUM with 3% of water content. This result is due to the difference of shear strength and stickiness of the soils in GUM. That is, it is considered that the shear strength and stickiness of soil when GUM contain 3% of water content are larger than when GUM contain 5% of water content. Because the stickiness increases, it is difficult to remove soils from the surface of aggregates.

Figure 50 shows the recovery of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 5% and 3% of water content in GUM, setting in the apparatus the same pipe inclination angle (25°) and amplitude of vibration (1cm).

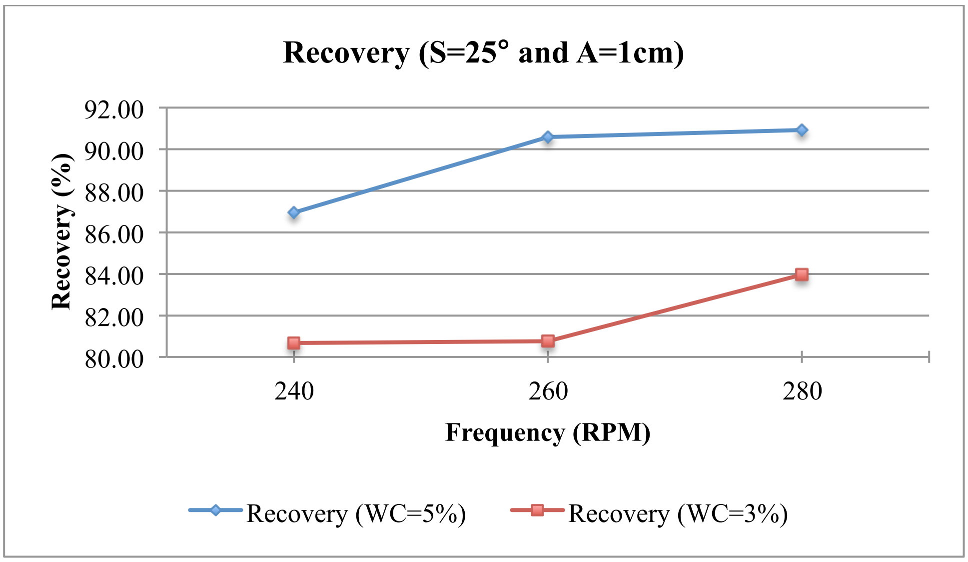

Fig. 50 Relationship between Recovery and Frequency (S=25, A=1cm with WC=5% and WC=3%)

It was confirmed from Figure 50 that the recovery of the processed materials inside the equipment also increased with increasing the frequency regardless of the water content in GUM. Furthermore, it was found that the recovery of GUM with 5% of water content was higher than when the GUM contain 3% of water content. From the results shown in Figure 50, it was concluded that it was more difficult to process the GUM with 3% of water content than when contain 5% of water content.

Figure 51 shows the attached material on the inner surface of the main pipe of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 5% and 3% of water content in GUM, setting in the apparatus the same pipe inclination angle (25°) and amplitude of vibration (1cm).

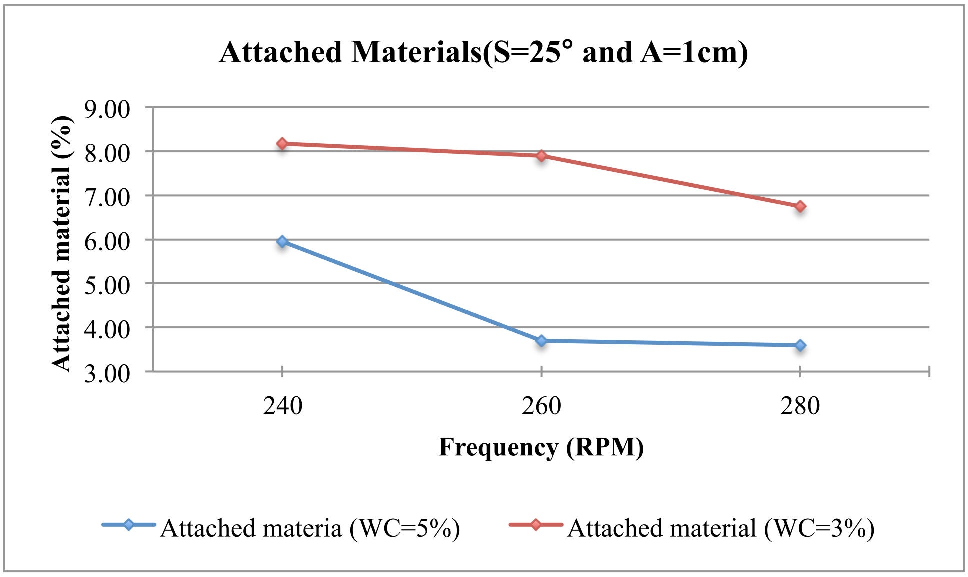

Fig. 51 Relationship between Attached Materials and Frequency (S=25, A=1cm with WC=5% and WC=3%)

It was confirmed from Figure 51 that the attached material decreased with increasing the frequency regardless of water content in GUM. The attached materials with 3% of water content in GUM were higher than when contain 5% of water content. These results prove that adhesion of GUM with 3% of water content was higher than when contain 5% of water content.

3.4.6 Experimental results (S = 15°, A = 1cm with WC = 5% and WC = 3%)

Figure 52 shows the percent of soil contained in GUM before and after the process inside the equipment, the figure in question shows the equipment performance when dealing with 5% and 3% of water content in GUM, setting in the apparatus the same pipe inclination angle (15°) and amplitude of vibration (1cm). The first 3 blue and orange columns (from left to right) correspond to 5% of water content in GUM, the others columns correspond to 3% of water content in GUM.

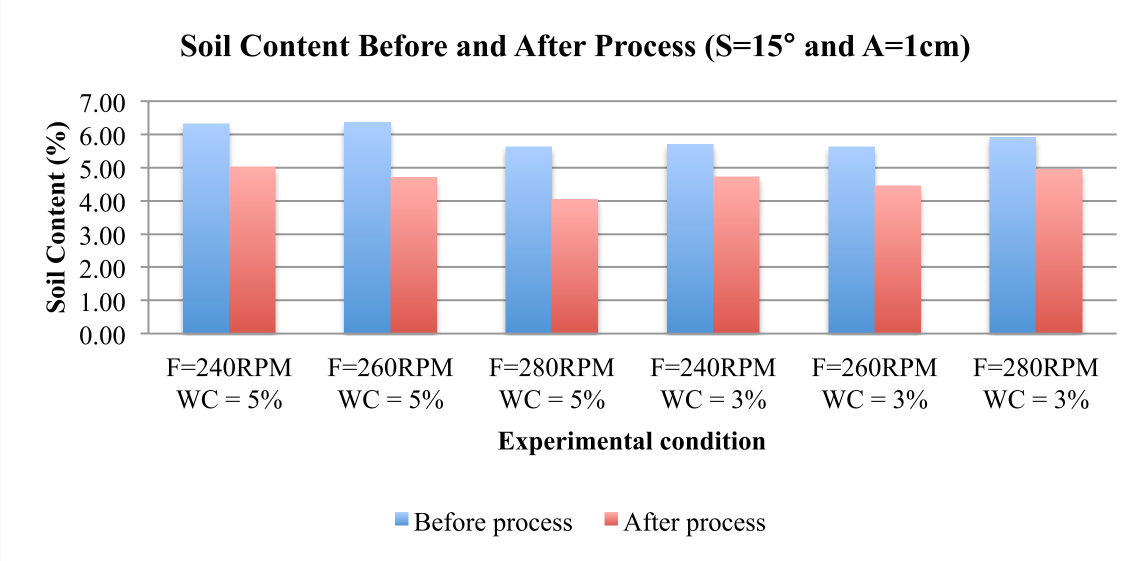

Fig. 52 Soil content before and after the process (S=15, A=1cm with WC=5% and WC=3%)

From the experimental results shown in Figures 52, it was possible to conclude that the equipment was able to reduce the soil content in GUM. This time, in the case of 5% water content although the soil contents in the GUM before the process inside the equipment did not satisfy the required value (less than 5%), the soil content in the processed aggregates, by the apparatus was reduced less than 5%, except under the experiment conditions of S=15°, A=1cm and F=240RPM that the soil content in the processed aggregates after the process inside the equipment was equal to 5.02%, even this value is higher than 5%, it is very close to the standard specification of quality as shown in Figure 52. On the other hand, in the case of 3% water content, although the soil contents in the GUM before the process inside the equipment did not satisfy the required value (less than 5%), the soil content in the processed aggregates, after the process inside the equipment was reduced less than 5% and satisfied the required value as shown in Figure 52. Even those experimental results, it is possible to notice that the difference between soil content in GUM, before process and after process inside the equipment is larger in the case of 5% of water content than 3% of water content. This fact means, that the equipment was able to reduce more the initial soil content in GUM when contain 5% of water content than 3% of water content. In this case, the final soil content in GUM when contain 3% and 5% of water content was less than 5% (required value), except in the case mentioned above.

Figure 53 shows the rate of suction of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 5% and 3% of water content in GUM, setting in the apparatus the same pipe inclination angle (15°) and vibration amplitude (1cm).

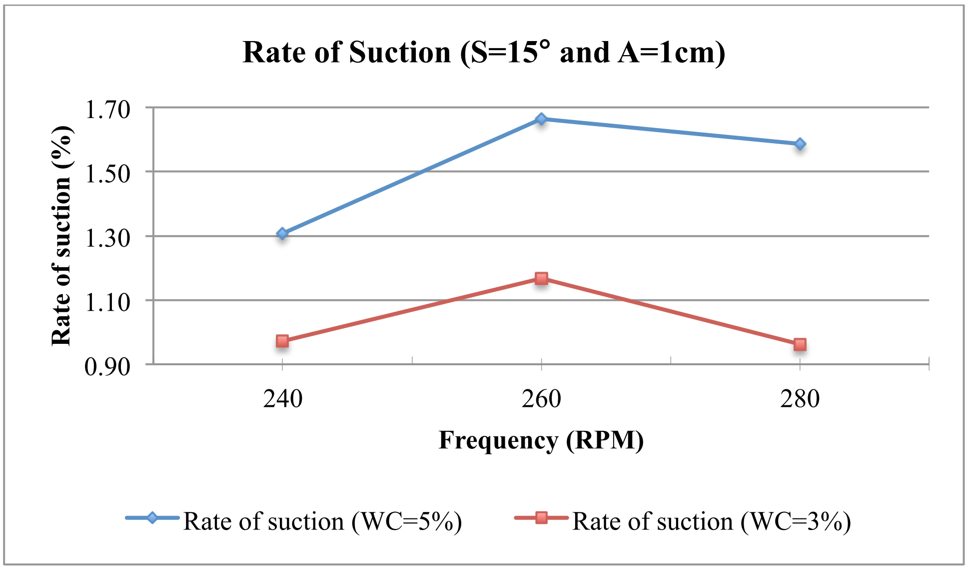

Fig. 53 Relationship between Rate of Suction and Frequency (S=15, A=1cm with WC=5% and WC=3%)

It was confirmed from Figure 53 that the equipment performance for GUM of 5% water content was higher than the equipment performance for GUM of 3% water content. This result is due to the difference of shear strength and stickiness of the soil in GUM. That is, it is considered that the shear strength and stickiness of soil is higher when GUM contain 3% of water content than when contain 5%.

Figure 54 shows the recovery of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 5% and 3% of water content in GUM, setting in the apparatus the same pipe inclination angle (15°) and vibration amplitude (1cm).

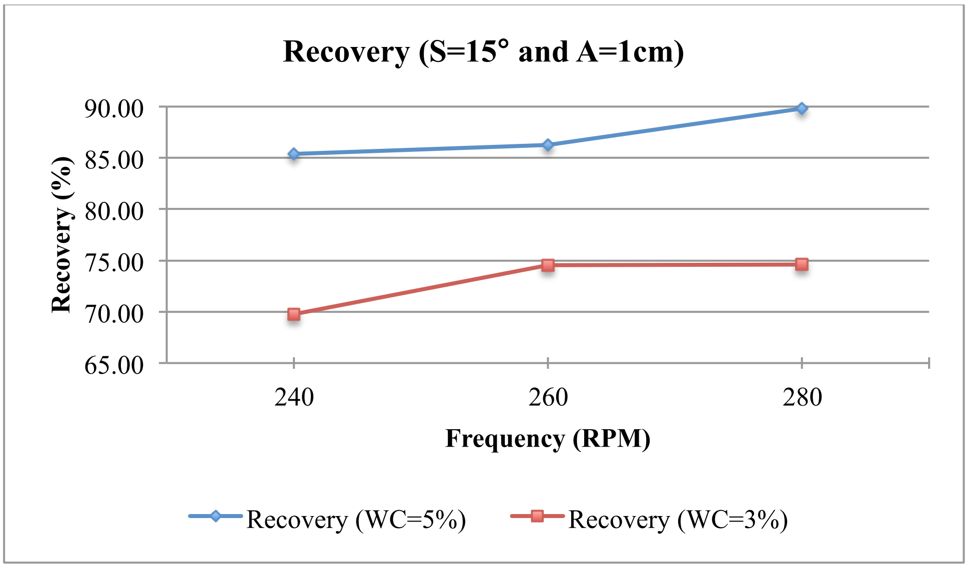

Fig. 54 Relationship between Recovery and Frequency (S=15, A=1cm with WC=5% and WC=3%)

It was confirmed from Figure 54 that the recovery of the processed materials inside the equipment also increased with increasing the frequency regardless of the water content in GUM. Furthermore, it was found that the recovery of GUM with 5% of water content was higher than when GUM contain 3% of water content. From the results shown in Figure 54, it was concluded that it was more difficult to process the GUM with 3% of water content than when contain 5% of water content as mentioned with the experiment conditions S=25°.

Figure 55 shows the attached material on the inner surface of the main pipe of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 5% and 3% of water content in GUM, setting in the apparatus the same pipe inclination angle (15°) and amplitude of vibration (1cm).

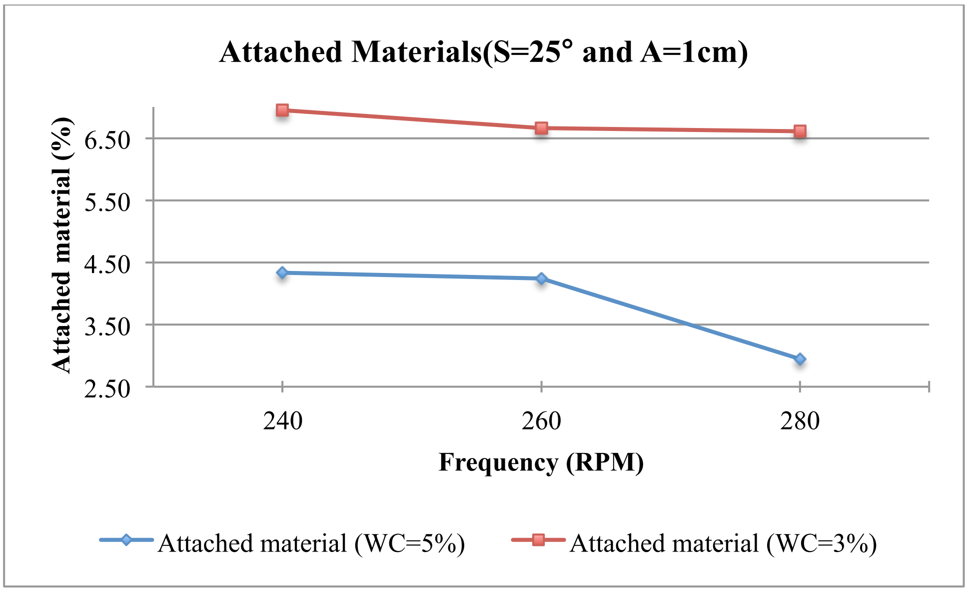

Fig. 55 Relationship between Attached Materials and Frequency (S=25, A=1cm with WC=5% and WC=3%)

It was confirmed from Figure 55 that the attached material decreased with increasing the frequency regardless of water content in GUM. The attached materials, when the equipment process the GUM with 3% of water content were higher than when GUM contain 5% of water content. These results prove that adhesion of GUM with 3% of water content was higher than when the GUM contain 5% of water content.

3.4.7 Experimental results (WC = 1% with A = 1, 3, 5cm and S = 20°, 25°)

Figure 56 shows the percent of soil contained in GUM before and after the process inside the equipment, the figure in question shows the equipment performance when dealing with 1% of water content in GUM, setting in the apparatus the same amplitude of vibration (1cm). The first 3 blue and orange columns (from left to right) correspond to 20° of pipe inclination angle, the others columns correspond to 25° of pipe inclination angle.

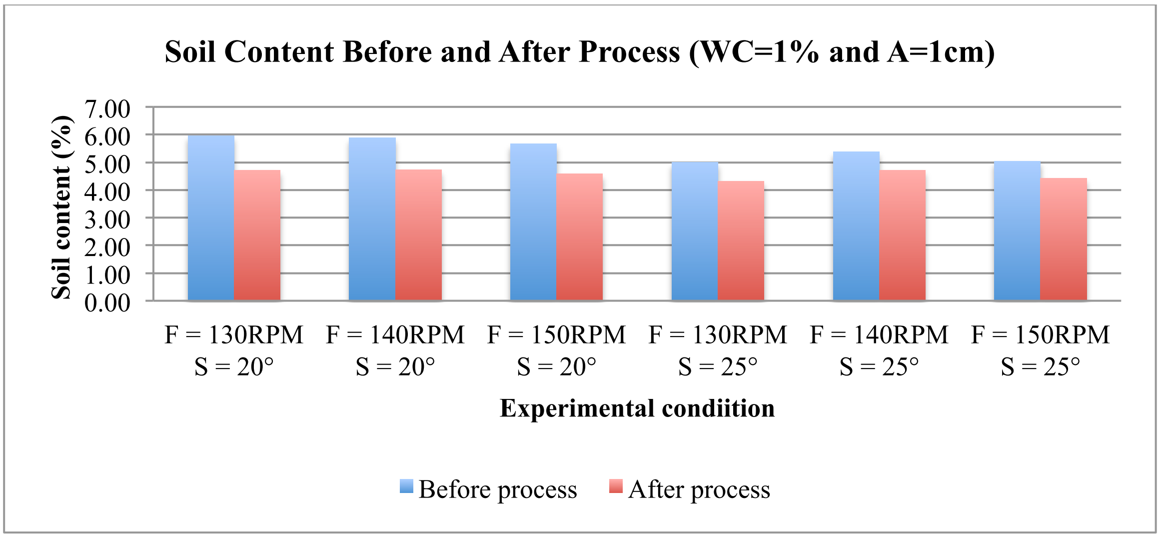

Fig. 56 Soil content before and after the process (WC=1% and A=1cm)

Figure 57 shows the percent of soil contained in GUM before and after the process inside the equipment, the figure in question shows the equipment performance when dealing with 1% of water content in GUM, setting in the apparatus the same amplitude of vibration (3cm). The first 3 blue and orange columns (from left to right) correspond to 20° of pipe inclination angle, the others columns correspond to 25° of pipe inclination angle.

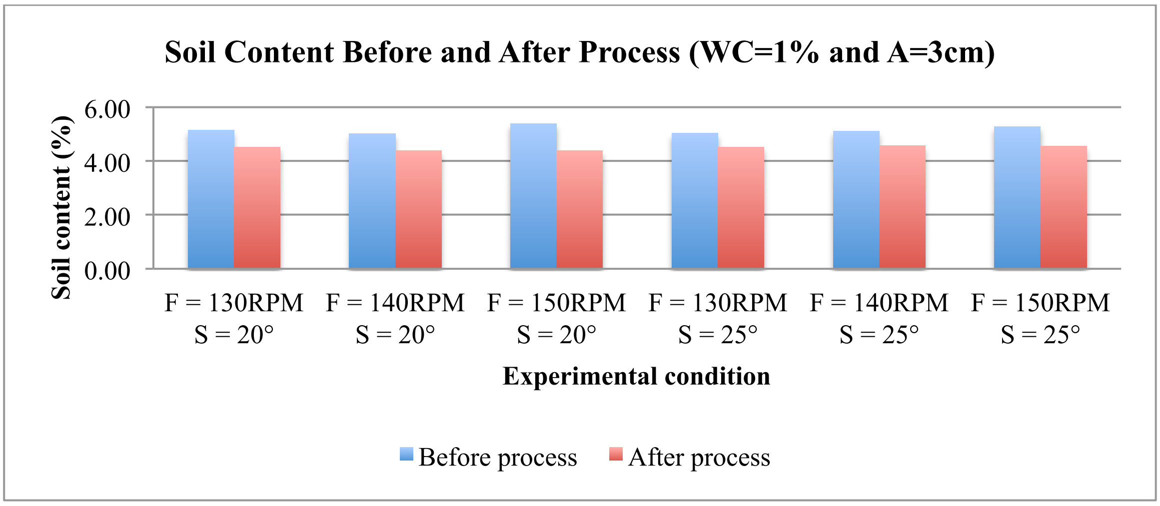

Fig. 57 Soil content before and after the process (WC=1% and A=3cm)

Figure 58 shows the percent of soil contained in GUM before and after the process inside the equipment, the figure in question shows the equipment performance when dealing with 1% of water content in GUM, setting in the apparatus the same amplitude of vibration (5cm). The first 3 blue and orange columns (from left to right) correspond to 20° of pipe inclination angle, the others columns correspond to 25° of pipe inclination angle.

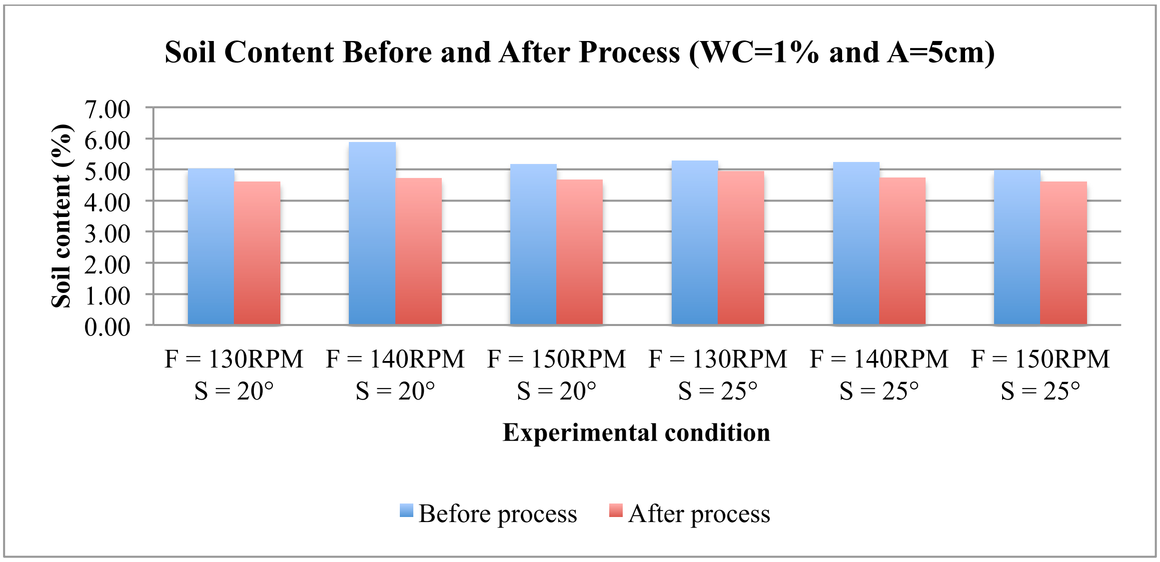

Fig. 58 Soil content before and after the process (WC=1% and A=5cm)

From the experimental results shown in Figures 56, 57 and 58, it was possible to conclude again that the equipment was able to reduce the soil content in GUM. As it is shown in those figures, in the case of 1% water content although the soil contents in the GUM before the process inside the equipment generally did not satisfy the required value (less than 5%), the soil content in the processed aggregates, after the process inside the apparatus was reduced less than 5%.

Even those experimental results, it is possible to notice that the difference between soil content in GUM, before process and after process inside the equipment is larger in the case of 20° of pipe inclination angle than 25° of pipe inclination angle, regardless the amplitude. This fact means, that the equipment was able to reduce more the initial soil content in GUM when pipe inclination angle was set at 20° than 25°.

Figure 59 shows the rate of suction of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 1% of water content in GUM.

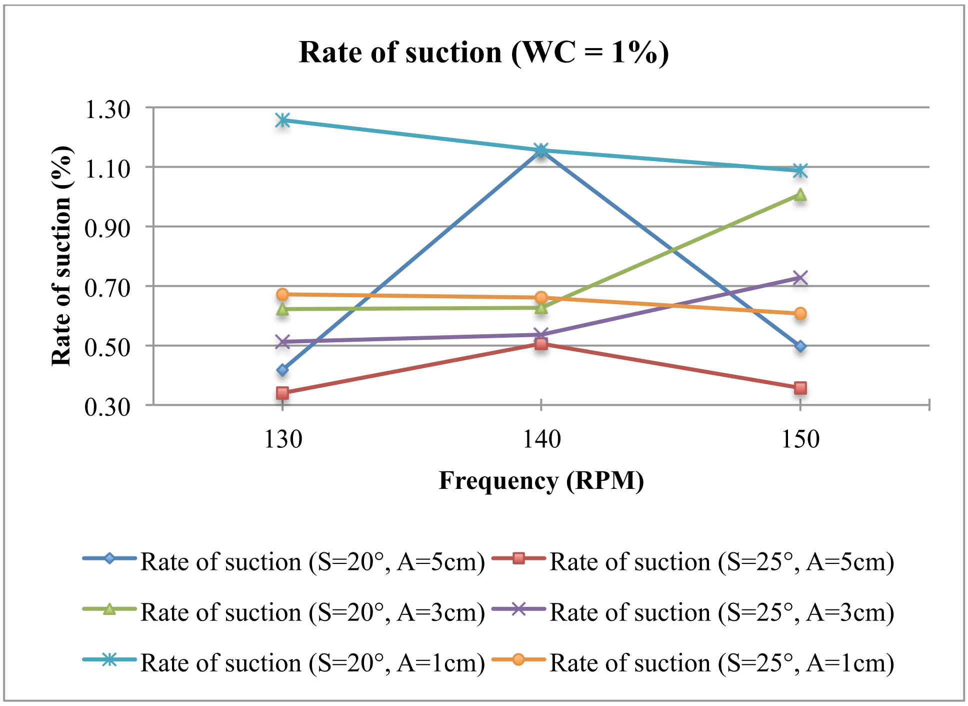

Fig. 59 Relationship between Rate of Suction and Frequency (WC=1%)

The experimental results that are shown in Figure 59 prove that the equipment performance (rate of suction) increases with decreasing the pipe inclination angle regardless the amplitude and frequency of vibration. It is also possible to notice that the equipment generally achieved its highest rate of suction with an amplitude equal to 1cm regardless the pipe inclination angle and frequency of vibration. Every experimental results that is shown in Figure 59 was obtained using samples of GUM containing 1 percent of water content, then the moisture content in the soil contained in GUM should be similar in each sample, therefore the stickiness of the soil in every sample should be similar too. Taking into consideration previous explanation, it is believe that, these differences among the experimental results was caused by different processing time for each sample, because pipe inclination angle and amplitude of vibration are two parameters with great influence in the processing time for GUM inside the apparatus.

Figure 60 shows the recovery of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 1% of water content in GUM.

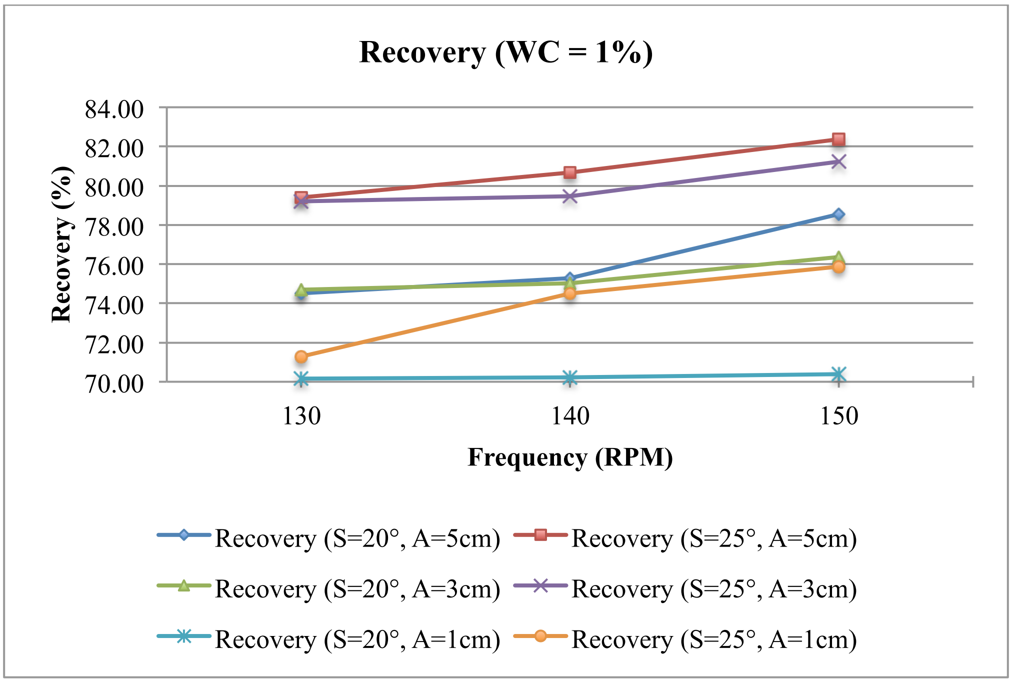

Fig. 60 Relationship between Recovery and Frequency (WC=1%)

It was notice from the experimental results shown in Figure 60, that recovery of processed material by the equipment increases with increasing the frequency of vibration regardless the amplitude and pipe inclination angle. It is also possible to realize that recovery of processed material by the equipment increases with increasing the pipe inclination angle, regardless the amplitude and frequency of vibration. Analyzing experimental results from another point of view, it is also possible to notice that recovery of processed material by the apparatus generally increases with increasing the amplitude of vibration regardless frequency of vibration and pipe inclination angle.

Figure 61 shows the attached material on the inner surface of the main pipe of the screenless separation equipment, the figure in question shows the equipment performance when dealing with 1% of water content in GUM.

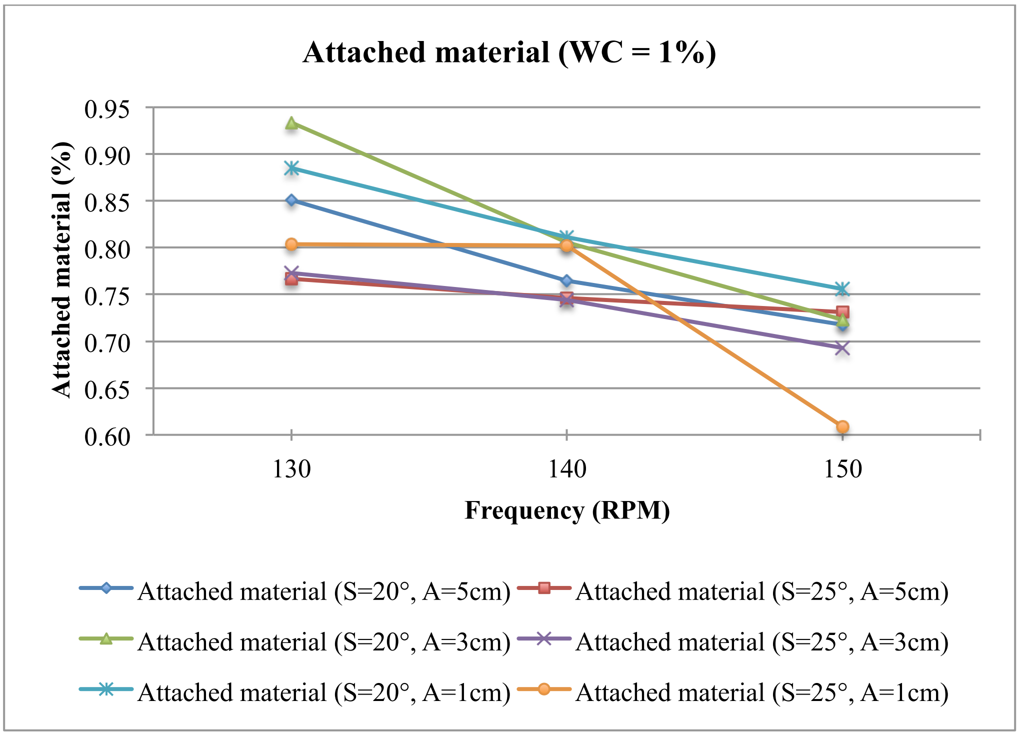

Fig. 61 Relationship between Attached Materials and Frequency (WC=1%)

After analyzing the experimental results shown in Figure 61, it is possible to conclude that attached material decreases with increasing the frequency of vibration regardless pipe inclination angle and amplitude of vibration. It is also possible to notice that attached material generally decreases with increasing the pipe inclination angle regardless frequency and amplitude of vibration. In the case of pipe inclination angle equal to 20 degrees, the lowest attached material values were obtained with amplitude equal to 5cm regardless the frequency of vibration, but in the case of pipe inclination angle equal to 25 degrees, there is no a clear tendency.

3.5 Summary of Chapter 3

Even it was proved through experiments that the equipment performance (rate of suction) increased compared to the previous equipment. It was also found that the performance of the newly proposed screenless separation equipment increased with increasing the water content in the GUM from 3% to 5%. This behaviour of equipment performance was opposite from previous equipment to current equipment.

That is, it was confirmed that the effect of water content in the GUM on the equipment performance was large and it should be investigated in detail to determine the optimum operation condition of this new equipment with a vibrating device.

Besides, the used materials to process (GUM) in each experiment (pervious equipment and newly proposed equipment) had different characteristics, because they were obtains from different construction sites. Moreover, even the reclaimed asphalt aggregate is obtained from the same construction site, its particles size distribution and water absorption can be different from one sample to another. Therefore, it is necessary to carry out experiments using the same sample of GUM, to guarantee the same characteristics in the material to process.

Even those mentioned facts, it can be drawn the following partial conclusions, taking into consideration the experimental results and analysis described in this chapter:

- It was proved the usefulness of the newly proposed screenless separation equipment, because improve the previous equipment performance.
- If high frequency with small amplitude of 1 cm is established in the equipment, it was possible to mitigate the adhesion properties of the fine particles that make up the GUM as a result of high water content.
- If the slope of the pipe is decreased in the equipment, it was possible to increase the equipment performance (rate of suction), regardless the frequency that was established in the equipment.
- Processed materials discharged from the newly screenless separation equipment satisfied the Japanese Standard for recycled aggregates and they can be used as recycled aggregate to produce asphalt concrete.
- Equipment performance generally increases when decreasing the amplitude of vibration.
- Pipe inclination angle and amplitude of vibration are two parameters with great influence in the processing time for GUM inside the apparatus.
- Recovery mainly depend on the frequency of vibration and pipe inclination angle.
- Attached materials on the inner surface of the pipe decreases when increasing the frequency of vibration.

CHAPTER 4 EXPERIMENTAL STUDY ON THE EFFECT OF WATER CONTENT ON REDUCTION OF SOIL CONTENT IN GUM WITH SAME EXPERIMENTAL CONDITIONS.

CHAPTER 4 EXPERIMENTAL STUDY ON THE EFFECT OF WATER CONTENT ON REDUCTION OF SOIL CONTENT IN GUM WITH SAME EXPERIMENTAL CONDITIONS.

4.1 Experimental apparatus

The experimental study on reduction of soil content in GUM setting the same conditions for experiment changing only the water content in the material to process, using the new proposed set of characteristics in the equipment was carried out in Takahashi Laboratory. The experimental apparatus used in this study was the same that was used in Chapter 2: Experimental study on Movement of Grizzly under Materials.

4.2 Experimental specimens used in this study

To carry out the experimental study on reduction of soil content in GUM setting the same conditions for experiment changing only the water content in the material to process in Takahashi Laboratory were used the recycled asphalt materials form Sendai Asphalt Plant of Maeda Road Construction Co., Ltd; and most of them did not match the required value for Amount of soils shown in Table 1 [8]. This time, the materials used in these experiments were 2 samples of GUM without soil, 2 kind of soils (two different percent of clay, from different construction site) and 2 different temperatures, increasing gradually the water content in every specific set of experimental conditions. Those materials were used in an attempt to elaborate in the laboratory a designed contaminated sample of GUM.

4.3 Experimental procedure

The experimental study on reduction of soil content in GUM trying to set the same conditions for experiments changing only the water content in the material to process was carried in Takahashi Laboratory. The procedure to measure the characteristics of every sample of GUM without soils (GUM-WS) was carried out as follows:

1. A sample of actual GUM (15 kg) was washed in the laboratory until the whole soil particles were removed from the surface of aggregates.
2. Particle size distribution and specific surface area of GUM-WS were measured according to Japanese Industrial Standard (JIS) A 1102, 2014 [32] and the formula of Manual: Asphalt Institute, 2015 [33], respectively.
3. GUM-WS was divided into fine aggregates and coarse aggregates by using sieve No.4.

4. Water absorption of the coarse aggregates and fine aggregates, was measured according to Japanese Industrial Standard (JIS) A 1110, 2006 [34] and Japanese Industrial Standard (JIS) A 1109, 2006 [35], respectively.
5. Water absorption of the whole GUM-WS sample (15 kg) was determined by considering the values obtained in step 4.

The procedure to measure the characteristics of every kind of soil attached on the surface of GUM was as follows:

1. Several samples of GUM (1000g) were washed in the laboratory. Soil particles suspended in the water were poured in the metal containers and then they were placed into the oven at 110°C to collect the soils.
2. Liquid limit, plastic limit and shrinkage limit of the collected soil were measured according to Japanese Geotechnical Society (JGS) 0142, 2009 [36], Japanese Industrial Standard (JIS) A 1205, 2009 [37], Japanese Geotechnical Society (JGS) 0145, 2009 [38], respectively.
3. Particle size distribution of soils was measured according to Japanese Industrial Standard (JIS) A 1204, 2009 [39] and Japanese Geotechnical Society (JGS)-0051, 2009 [40].

After the characteristics of every sample of GUM-WS and every sample of pure soils were measured, the experiments on reduction of soil content in GUM were carried out. The procedure of the experiments on reduction of soil content in GUM was as follows:

1. 3 samples of GUM-WS (2057g dried mass) and 3 samples of soil (143g dried mass) were dried in the oven and then they were mixed, to obtain 3 mixture samples of GUM-WS and soil (2200g dried mass). The soil content in the mixtures of GUM-WS and soil was set to be 6.5% (143/2200x100).
2. A load of 15kg was placed on each mixed sample of GUM-WS and soils, for 24 hours to simulate the storage conditions at construction site. The load consist on a bag with aggregate. After 24 hours the load was removed.
3. The pipe inclination angle was set at 15 degrees. The large compressor and suction machine were started. Then, the vibration device was started. Its frequency and amplitude were set to be 260 RPM and 1cm, respectively. The temperature was kept to be 25°C and 15°C in the laboratory.

4. A certain amount of water was poured into each mixed sample of GUM-WS and soil (the prepared mixed sample of GUM-WS and soil in step 1) to obtain a desired water content. Table 2 shows 3 examples of those mixtures.
5. Each mixed sample of GUM-WS and soil with water was fed into the equipment twice to simulate two suction places.
6. Mixed sample discharged from the equipment was collected and soil content was measured according to Japanese Industrial Standard (JIS) A 1103, 2014 [31]. The same experiments were carried out 3 times and then the average of soil content was obtained.
7. A difference between the initial soil content and the one after processing, was calculated to check the performance of the apparatus to reduce the soil content in the designed mixed sample.

The procedure was repeated from step 1 to step 7 with increasing the water content in the mixed sample of GUM-WS and soil as shown in Table 2, until finish all experiments with every combination of material and temperature. Water content in the mixed sample of GUM-WS and soil was changed by 5% respect to the soil mass until 50%. After 50%, it was changed by 10% respect to the soil mass.

After finishing previous procedures, the software RStudio version 0.99.887 was used to carry out a statistical analysis of experimental results. The analysis was carried out as follows:

1. Determining the fitted curve of each set of data. Then, using the obtained curve, the water content was changed by 0.065% to increase the amount of values in every set of data.
2. Analysing the normality distribution of every obtained set of data from the fitted curve.
3. Analysing if difference arise between two obtained set of data. If the two obtained set of data are not normally distributed, Wilcoxon Signed Rank Test will be used to compare them. In case of the two obtained set of data are normally distributed, Student's t-test will be used to compare them.

Table 2 Preparation of mixed samples of GUM-WS and soil (3 first samples)

Dried mix sample mass (GUM-WS+soil) (g)	Soil content in the mix (GUM-WS+soil) (%)	Dried sample mass (GUM-WS) (g)	Dried sample mass (soil) (g)	Water content in the mix (GUM-WS+soil) respect to soil (%)	Amount of water to pour into the mix (GUM-WS+soil) (g)	Water content in the mix respect to total mass (GUM-WS+soil) (%)
2200	6.5	2057	143	5.0	7.15	0.325
2200	6.5	2057	143	10.0	14.30	0.650
2200	6.5	2057	143	15.0	21.45	0.975

4.4 Results and discussion

4.4.1 Soil properties.

Table 3 shows the percentage of clay, silt, sand and gravel that makes up the two kinds of soils used in the experiments.

Table 3 Soils composition

Kind of particles	Soil composition (Soil 1)	Soil composition (Soil 2)
Clay (less than 5μm)	1.2%	11.1%
Silt (5μm – 75μm)	93.6%	67.1%
Sand (75μm – 2000μm)	5.2%	21.8%
Gravel (more than 2000μm)	0%	0%

Table 4 shows the Atterberg Limits. The liquid limit, plastic limit and shrinkage limit of collected soils were measured according to Japanese Geotechnical Society (JGS) 0142, 2009 [36], Japanese Industrial Standard (JIS) A 1205, 2009 [37] and Japanese Geotechnical Society (JGS) 0145, 2009 [38].

Table 4 Atterberg limits of soils used in the experiments

Atterberg Limits	Soil 1	Soil 2
Liquid Limit (%)	37.0%	48.1%
Plastic Limit (%)	-	-
Shrinkage Limit (%)	26.9%	22.1%

4.4.2 GUM-WS properties.

The particle size distribution of GUM-WS was measured according to Japanese Industrial Standard (JIS) A 1102, 2014 [32]. Table 5 shows the results related with the 2 samples of GUM-WS.

Table 5 Particle size distribution of GUM-WS

Sieves (#)	Cumulative rate (%)									
	16.00 mm (5/8in)	12.7 mm (1/2in)	9.5 mm (3/8in)	4.75 mm (#4)	2.36 mm (#8)	1.18 mm (#16)	0.60 mm (#30)	0.30 mm (#50)	0.15 mm (#100)	0.075 mm (#200)
Sample of GUM-WS1	100.0	99.7	91.00	55.0	30.9	16.4	7.63	2.78	0.67	0.10
Sample of GUM-WS2	100	99.5	92.72	62.46	38.82	22.35	10.80	4.04	1.01	0.15

To determine the specific surface area of GUM-WS, the formula of Asphalt Institute, 2015 [33] was used. This formula is shown below:

$SA = 2 + 0.02a + 0.04b + 0.08c + 0.14d + 0.3e + 0.60f + 1.60g$ (4)

where, a, b, c, d, e, f and g represent the percent of total aggregate passing the #4, #8, #16, #30, #50, #100, #200 sieves, respectively. The value from this formula is obtained in ft^2/lb. Then, after substitute the corresponding values in the formula, the specific surface area of GUM-WS was obtained as follows:

$SA_1 = 8.11\, ft^2/lb = 1.66\, m^2/kg$ (5)

$SA_2 = 10.16\, ft^2/lb = 2.08\, m^2/kg$ (6)

To determine the water absorption of each sample of GUM-WS, first, it was necessary to separate the coarse aggregates from fine aggregates because the water absorption of fine aggregates and the one of coarse aggregates were measured according to Japanese Industrial Standard (JIS) A 1109, 2006 [35] and Japanese Industrial Standard (JIS) A 1110, 2006 [34], respectively. Table 6 shows the measured water absorption related with the 2 sample of GUM-WS.

Table 6 Water absorption of GUM-WS

Water absorption of GUM-WS			
	Fine aggregate (%)	Coarse aggregate (%)	GUM-WS (%)
GUM-WS1	1.784	1.629	1.714
GUM-WS2	1.888	1.710	1.821

The mass of mixed sample of GUM-WS and soil was selected taking into consideration the Japanese Industrial Standard (JIS) A 1103, 2014 [31] to determine the amount of materials passing the standard sieve 75 μm (#200) in the recycled aggregates.

4.4.3 Experimental results. Same GUM

Figure 62 shows the percent of soil contained in GUM before and after the process inside the equipment, the figure in question shows the equipment performance when dealing with GUM-WS1, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Water content in the mixed sample of GUM-WS1 and soil was changed by 5% respect to the soil mass until 50%. After 50%, it was changed by 10% respect to the soil mass. In Figure 62, black bar "Before Process" represent the soil content of GUM-WS1 before process in the equipment. In the case of green bar "G1T15S1. A Process", brown bar "G1T15S2. A Process", blue bar "G1T25S1. A Process", orange bar "G1T25S2. A Process", represent the soil content of GUM-WS1 after the process in the equipment, with temperature 15°C and soil 1, temperature 15°C and soil 2, temperature 25°C and soil 1, and temperature 25°C and soil 2 respectively. Red line "Target Value" represents the percent that soil content in the processed recycled asphalt aggregate should be lower than this value respectively.

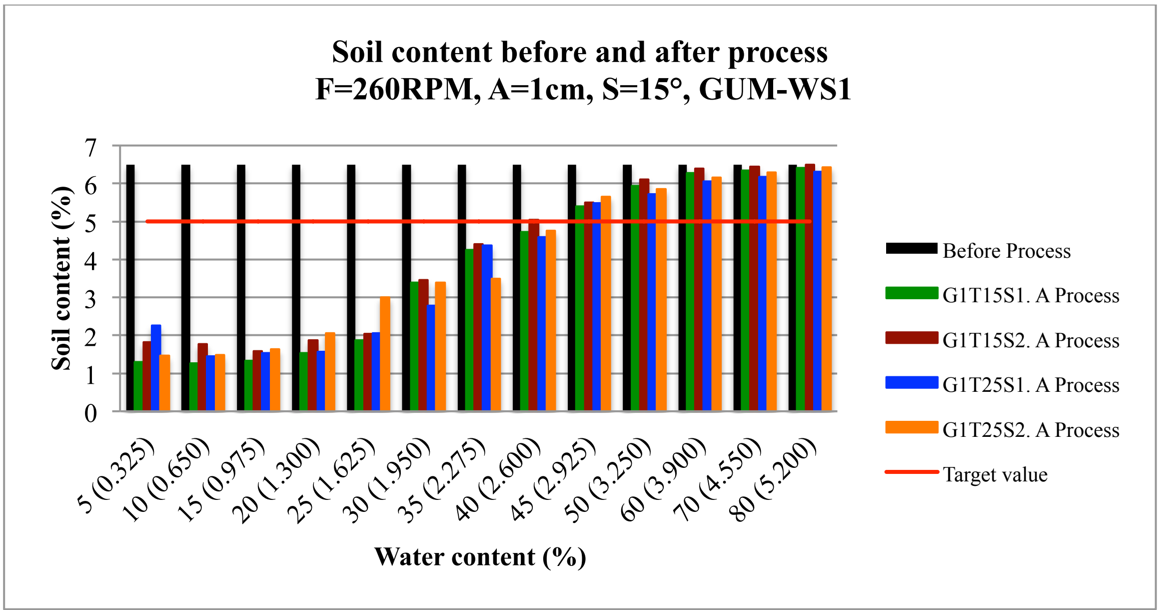

Fig. 62 Soil content before and after the process (F=260RPM, A=1cm, S=15 and GUM-WS1)

From the experimental results shown in Figure 62, it was possible to conclude that the equipment was able to reduce the percent of soil contained in the mixture of GUM-WS1 and soil less than 5%, required value from [8], from 5% to 40% of water content respect to the amount of soil, regardless the temperature in the laboratory and the kind of soil, except for "G1T15S2", that the mentioned parameter was lower than 5% from 5% to 35% of water content. It is also possible to conclude that, lower percent of soils contained in the processed recycled asphalt aggregate, after the process in the equipment, were mainly obtained from

10% to 15% of water content respect to the amount of soil, regardless the temperature in the laboratory and the kind of soil. This fact means that, the equipment was able to reduce more the initial soil content in the material to process when the mixture of GUM-WS1 and soil contain 10% or 15% of water content respect to the amount of soil, regardless the temperature in the laboratory and the kind of soil. On the other hand, the percent of soil contained in the mixture of GUM-WS1 and soil after the process in the equipment, from 20% to 80% of water content respect to the amount of soil, increases regardless the temperature in the laboratory and the kind of soil. This fact means that, the equipment capacity to reduce the initial soil content in the asphalt materials to process, when they contain from 20% to 80% of water content respect to amount of soil, decreases regardless the temperature in the laboratory and the kind of soil.

Figure 63 shows the percent of soil contained in GUM before and after the process inside the equipment, the figure in question shows the equipment performance when dealing with GUM-WS2, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Water content in the mixture to process was changed, following the procedure explained before. In Figure 63, black bar "Before Process" represents the soil content of GUM-WS2 before process in the equipment. In the case of green bar "G2T15S1. A Process", brown bar "G2T15S2. A Process", blue bar "G2T25S1. A Process", orange bar "G2T25S2. A Process", represent the soil content of GUM-WS2 after the process in the equipment, with temperature 15°C and soil 1, temperature 15°C and soil 2, temperature 25°C and soil 1, and temperature 25°C and soil 2 respectively. Red line "Target Value" represents the percent that soil content in the processed recycled asphalt aggregate should be lower than this value respectively.

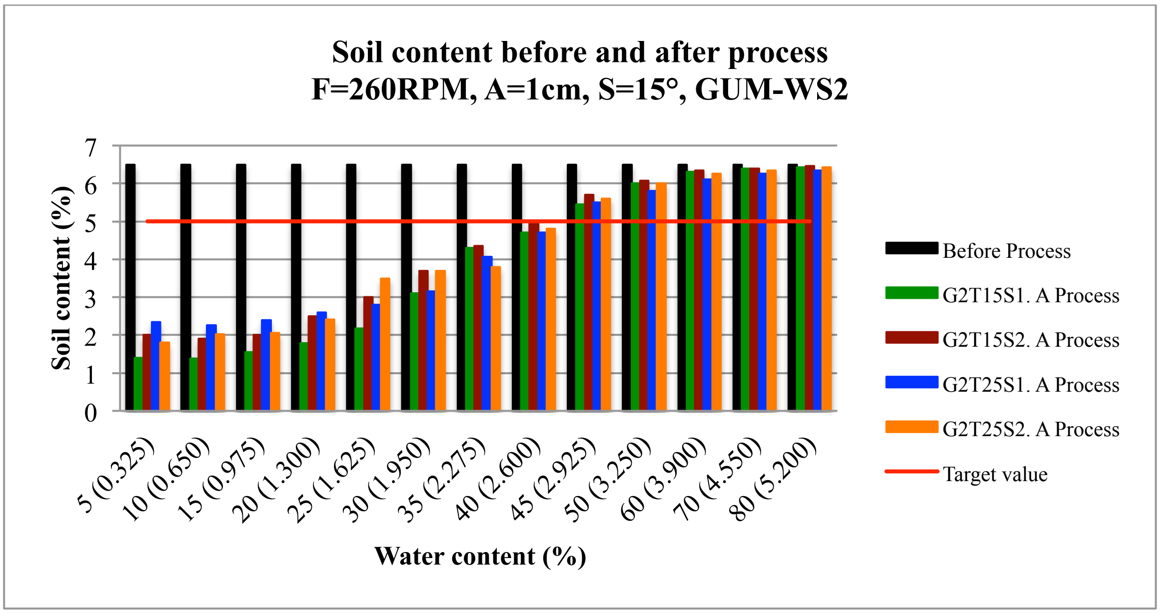

Fig. 63 Soil content before and after the process (F=260RPM, A=1cm, S=15 and GUM-WS2)

From the experimental results shown in Figure 63, it was possible to conclude that the equipment was able to reduce the percent of soil contained in the mixture of GUM-WS2 and soil less than 5%, required value from [8], from 5% to 40% of water content respect to the amount of soil, regardless the temperature in the laboratory and the kind of soil, except for "G2T15S2", that the mentioned parameter was lower than 5% from 5% to 35% of water content. It is also possible to conclude that, lower percent of soils contained in the processed recycled asphalt aggregate, after the treatment in the equipment, were mainly obtained from 5% to 15% of water content respect to the amount of soil, regardless the temperature in the laboratory and the kind of soil. This fact means that, the equipment was able to reduce more the initial soil content in the material to process when the mixture of GUM-WS2 and soil contain from 5% to 15% of water content respect to the amount of soil, regardless the temperature in the laboratory and the kind of soil. On the other hand, the percent of soil contained in the mixture of GUM-WS2 and soil after the process in the equipment, from 20% to 80% of water content respect to the amount of soil, increases regardless the temperature in the laboratory and the kind of soil. This fact means that, the equipment capacity to reduce the initial soil content in the asphalt materials to process, when they contain from 20% to 80% of water content respect to amount of soil, decreases regardless the temperature in the laboratory and the kind of soil.

Figure 64 shows the rate of suction of the equipment, the figure in question shows the equipment performance when dealing with GUM-WS1, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle

(15°). Water content in the mixture to process was changed, following the procedure explained before. In Figure 64, blue line “G1T15S1. RS”, red line “G1T15S2. RS”, green line “G1T25S1. RS”, violet line “G1T25S2. RS” represent the rate of suction (RS) of the equipment when processing the GUM-WS1 with temperature 15°C and soil 1, temperature 15°C and soil 2, temperature 25°C and soil 1, temperature 25°C and soil 2 respectively.

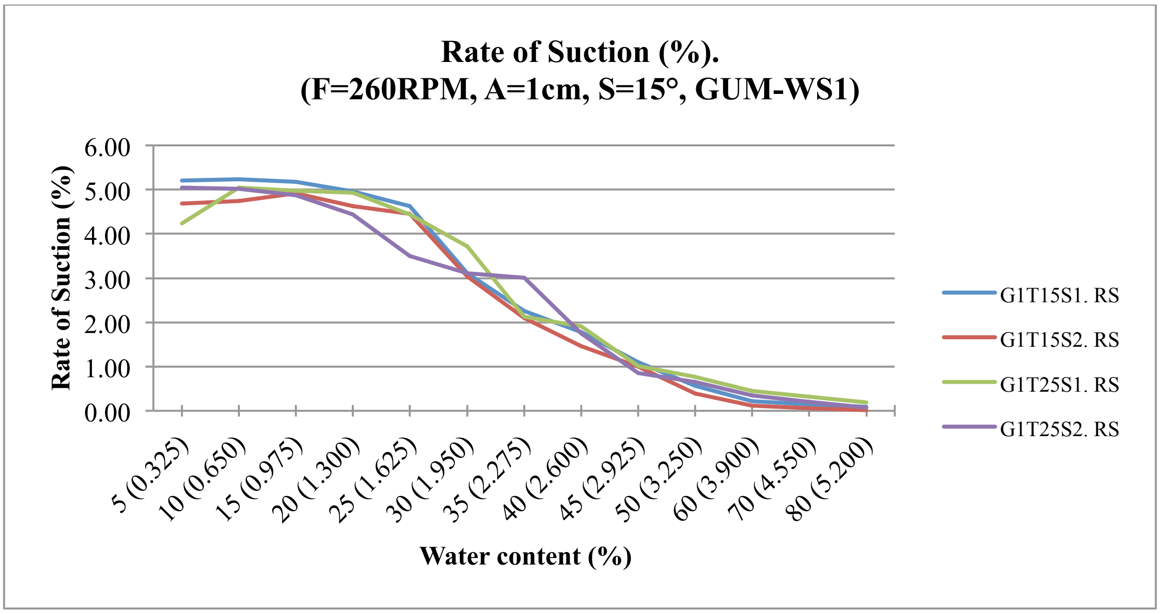

Fig. 64 Relationship between Rate of Suction and Water Content (F=260RPM, A=1cm, S=15 and GUM-WS1)

From the analysis of the experimental results shown in Figure 64, it is possible to conclude that the rate of suctions of the equipment from 5% to 15% of water content respect to the amount of soil keep mainly stable, regardless of the temperature in the laboratory and the kind of soil. This fact means that the stickiness capacity of soil contained in GUM keeps stable from 5% to 15% of water content respect to the amount of soil and somewhat low. Besides, the equipment achieved its higher rate of suctions in the mentioned rage of water content (from 5% to 15%) regardless the temperature in the laboratory and the kind of soil. On the other hand, the rate of suction of the equipment from 20% to 80% of water content respect to the amount of soil decreases regardless the temperature in the laboratory and the kind of soil. This fact means that, the stickiness capacity of soil contained in GUM increases from 20% to 80% of water content respect to amount of soil regardless the temperature in the laboratory and the kind of soil.

The researcher thinks that, the previous mentioned behaviour of equipment performance (rate of suction) is because stick limit of the soil. The sticky limit was defined by Atterberg as the lowest water content at which the soil sticks to the blade of a metal spatula when the spatula is drawn against the surface of the remoulded soil sample [41]. It means that, soils have a specific water content from where sticks to metal spatula, therefore, soils also have a specific water content from where sticks to recycled asphalt aggregate. Those mentioned water contents, should not be the same because the surface of metal spatula and recycled asphalt aggregate have different characteristics.

Figure 65 shows the rate of suction of the equipment, the figure in question shows the equipment performance when dealing with GUM-WS2, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Water content in the mixture to process was changed, following the procedure explained before. In Figure 65, blue line “G2T15S1. RS”, red line “G2T15S2. RS”, green line “G2T25S1. RS”, violet line “G2T25S2. RS” represent the rate of suction of the equipment when processing the GUM-WS2 with temperature 15°C and soil 1, temperature 15°C and soil 2, temperature 25°C and soil 1, temperature 25°C and soil 2 respectively.

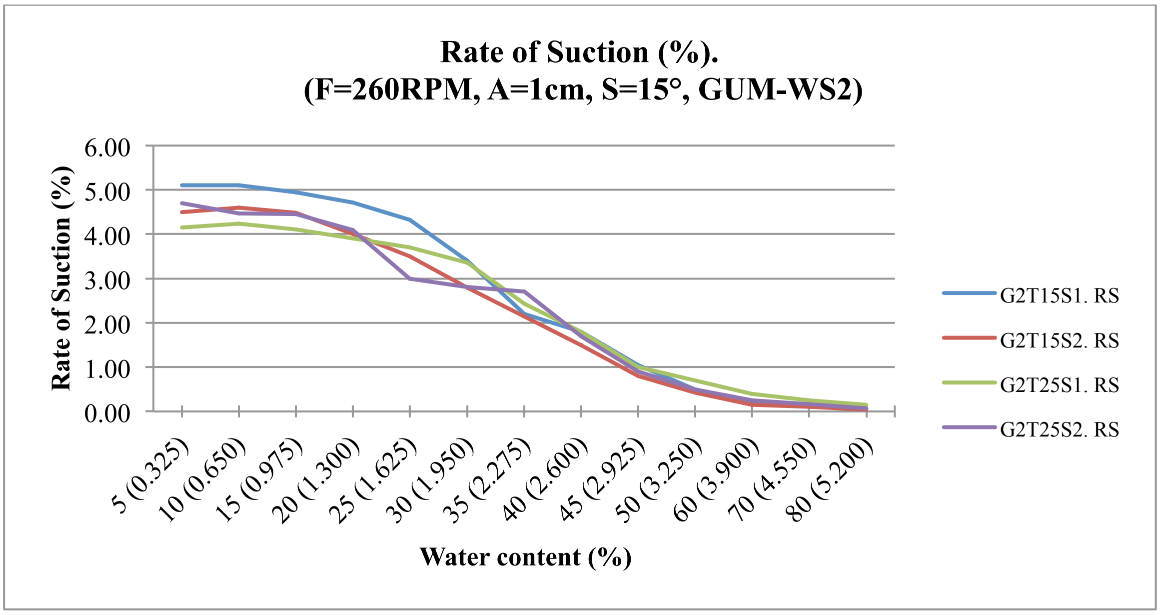

Fig. 65 Relationship between Rate of Suction and Water Content (F=260RPM, A=1cm, S=15 and GUM-WS2)

Analyzing the experimental results shown in Figure 65, it is possible to notice that the rate of suctions of the equipment from 5% to 15% of water content respect to the amount of soil keep mainly stable, regardless of the temperature in the laboratory and the kind of soil. This fact means that the stickiness capacity of soil contained in GUM keeps stable from 5% to 15% of water content respect to the amount of soil and somewhat low. Furthermore, the rate of suction of the equipment in the case of “G2T15S1. RS” was a little bit higher than the other 3 values of the mentioned parameter, from 5% to 25% of water content respect to soil mass. Besides, the equipment achieved its higher rate of suctions in the rage of water content from 5% to 15%, respect to the soil mass, regardless the temperature in the laboratory and the kind of soil. On the other hand, the rate of suction of the equipment from 20% to 80% of water content respect to the amount of soil decreases regardless the temperature in the laboratory and the kind of soil. This fact means that, the stickiness capacity of soil contained in GUM increases from 20% to 80% of water content respect to amount of soil regardless of the temperature in the laboratory and the kind of soil.

In an attempt to explain the behaviour of equipment performance in the case of "G2T15S1. RS" the researcher was analyzing the characteristics of experimental conditions and the used materials in the experiment. It is known that many factors have influence on equipment performance (rate of suction), but one of the most import is the stickiness capacity of the soil. [42], carried out a research on effect of temperature on adhesion of clay soil to steel. They reported that with increasing in temperature from 5ºC to 30ºC, the adhesion of clay soil was decreased about 82%. Therefore, taking into consideration only this conclusion, the equipment performance (rate of suction) should increases with increasing the temperature to carry out the experiment. But, while increasing the temperature in the experiment, the asphalt binder contained in the recycled asphalt aggregate can get a softer state than before due to the high temperature, then the asphalt binder under this state causes that soil contained in GUM can sticks easier to the aggregate surface covered by asphalt binder than before. Therefore, the temperature can has a double effect on equipment performance and the final result will depend on the characteristics of the materials to process.

Moreover, recycled asphalt aggregates are composed by grain totally covered, partially covered and non-covered with asphalt binder as it is shown in Figure 66. Even, it is used in the experiment, the same big sample of GUM-WS (15kg), it is difficult to assure that every experiment is carried out with the exactly same sample of GUM-WS (2057g dried mass) with the exactly same specific surface area and water absorption. Then, the covered surface area with asphalt binder in the recycled asphalt aggregate should be a little bit different from one sample (GUM-WS, 2057 dried mass) to another. Then, if the temperature increases and the covered surface area with asphalt binder increases too, in GUM, these previous conditions can reduces the equipment performance.

Fig. 66 Photograph of GUM

Kooistra, Verhoef, Broere, Ngan-Tillard, & van Tol, [43], carried out a research on appraisal of stickiness of natural clays from laboratory tests. They reported that, sticking of clay is a complex phenomenon which results from the interaction of clay with the contact surfaces. Besides, they confirmed that, a clay is a multi-phase material and its behaviour depends on numerous parameters such as: clay fraction, silt fraction, sand fraction, water content, Atterberg limits, degree of consolidation and stress state. Therefore, soil particles size distribution and water content in the soil can affect the soil stickiness and then they can affect the equipment performance too.

Even, in Figure 64 and 65 the experiments were carried out with different GUM-WS, keeping constant temperature in the laboratory and the kind of soil, the experimental results had the same tendency, when increasing the water content in the material to process.

Figure 67 shows the recovery of the equipment, the figure in question shows the equipment performance when dealing with GUM-WS1, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Water content in the mixture to process was changed, following the procedure explained before. In Figure 67, blue line “G1T15S1. Rec”, red line “G1T15S2. Rec”, green line “G1T25S1. Rec”, violet line “G1T25S2. Rec” represent the recovery of the equipment when processing the GUM-WS1 with temperature 15°C and soil 1, temperature 15°C and soil 2, temperature 25°C and soil 1, temperature 25°C and soil 2 respectively.

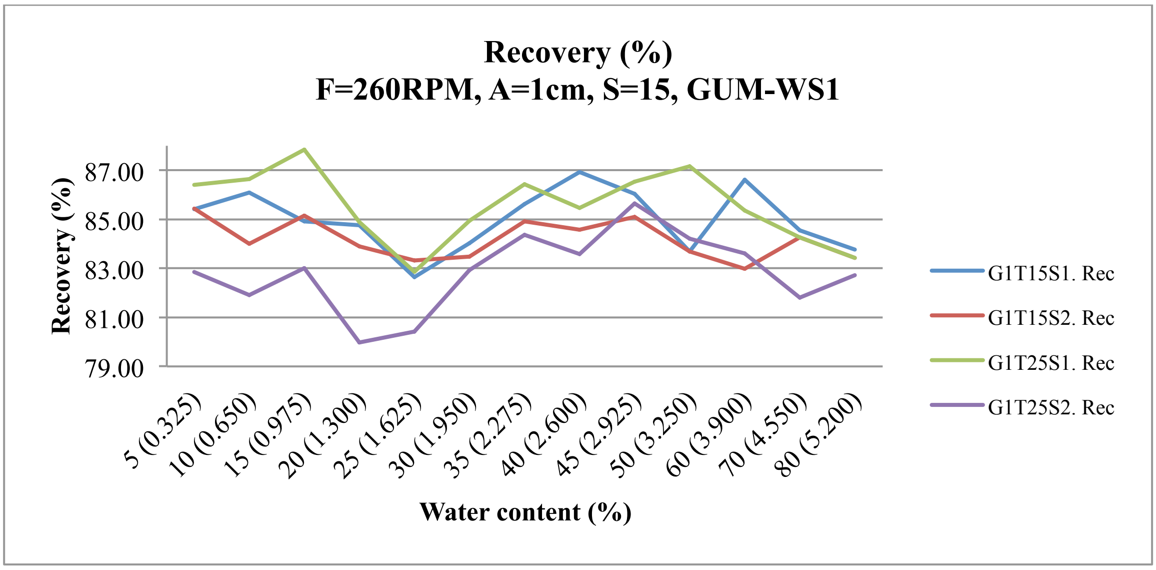

Fig. 67 Relationship between Recovery and Water Content (F=260RPM, A=1cm, S=15 and GUM-WS1)

Analyzing the experimental results shown in Figure 67, it is possible to realize that recovery of the equipment from 5% to 80% of water content respect to the amount of soil did not keep a defined tendency, regardless the temperature in the laboratory and the kind of soil. This fact means that, even it was kept constant the temperature and the kind of soil, increasing the water content in the material to process, the equipment performance did not have a defined tendency. Then, the temperature, the kind of soil and the water content do not have a great influence on the equipment recovery. Therefore, it is confirmed that recovery mainly depends on frequency of vibration and pipe inclination angle.

Figure 68 shows the recovery of the equipment, the figure in question shows the equipment performance when dealing with GUM-WS2, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Water content in the mixture to process was changed, following the procedure explained before. In Figure 68, blue line "G2T15S1. Rec", red line "G2T15S2. Rec", green line "G2T25S1. Rec", violet line "G2T25S2. Rec" represent the recovery of the equipment when processing the GUM-WS2 with temperature 15°C and soil 1, temperature 15°C and soil 2, temperature 25°C and soil 1, temperature 25°C and soil 2 respectively.

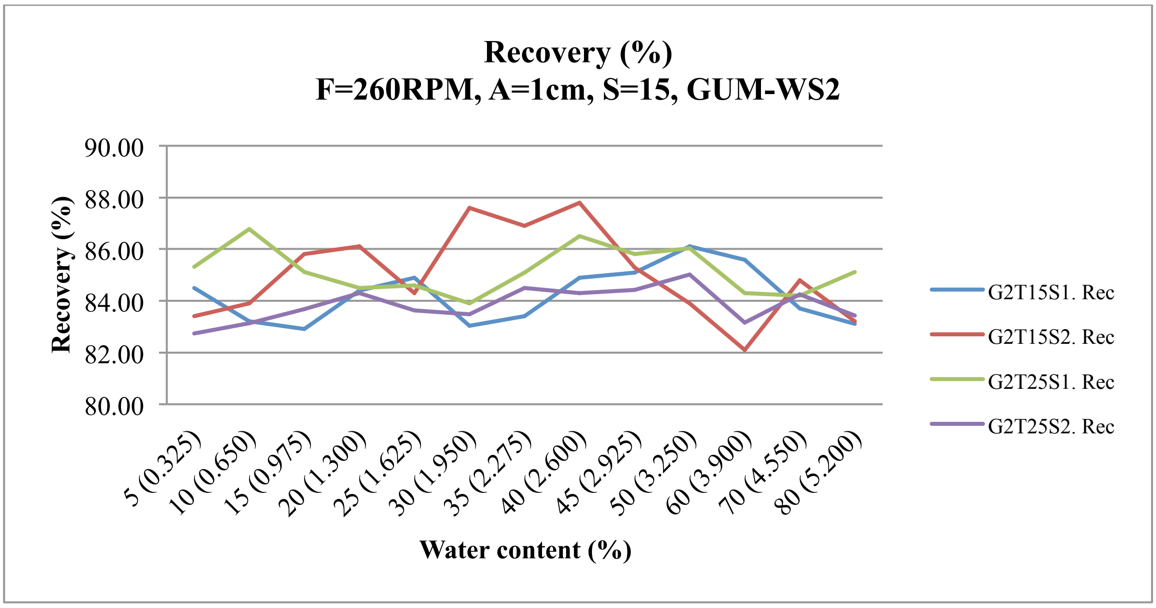

Fig. 68 Relationship between Recovery and Water Content (F=260RPM, A=1cm, S=15 and GUM-WS2)

Analyzing the experimental results shown in Figure 68, it is possible to realize that recovery of the equipment from 5% to 80% of water content respect to the amount of soil did not keep a defined tendency, regardless the temperature in the laboratory and the kind of soil. This fact means that, even it was kept constant the temperature and the kind of soil and increasing the water content in the material to process, the equipment performance did not have a defined tendency. Then, the temperature, the kind of soil and the water content do not have a great influence on the equipment recovery. Therefore, it is confirmed that recovery mainly depends on frequency of vibration and pipe inclination angle.

Even, in Figure 67 and 68 the experiments were carried out with different GUM-WS, keeping constant temperature in the laboratory and the kind of soil, the experimental results had the same tendency, when increasing the water content in the material to process.

Figure 69 shows the attached materials on the inner surface of the main pipe of the equipment, the figure in question shows the equipment performance when dealing with GUM-WS1, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Water content in the mixture to process was changed, following the procedure explained before. In Figure 69, blue line “G1T15S1. Attach”, red line “G1T15S2. Attach”, green line “G1T25S1. Attach”, violet line “G1T25S2. Attach” represent the attached materials on the inner surface of the main pipe of the equipment when processing the GUM-WS1 with temperature 15°C and soil 1, temperature 15°C and soil 2, temperature 25°C and soil 1, temperature 25°C and soil 2 respectively.

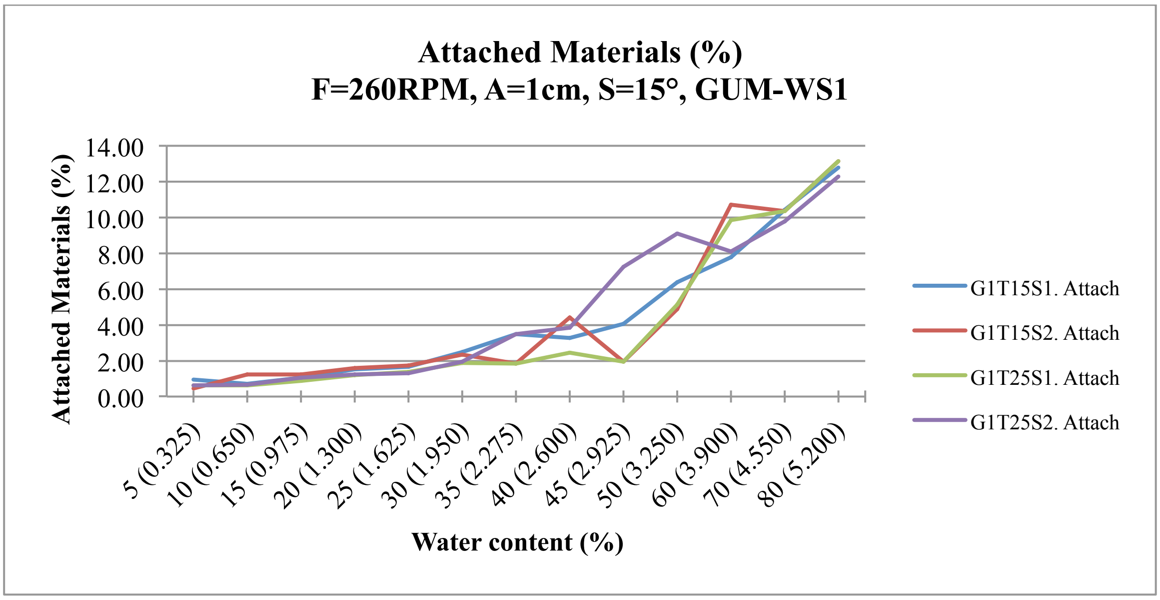

Fig. 69 Relationship between Attached Materials and Water Content (F=260RPM, A=1cm, S=15 and GUM-WS1)

Analyzing the experimental results shown in Figure 69, it is possible to notice that the attached materials on the inner surface of the main pipe of the equipment from 5% to 80% of water content respect to the amount of soil has a tendency of increasing while increasing the water content in the material to process, regardless of the temperature in the laboratory and the kind of soil. This fact proves, water content has a great influence on the previous mentioned parameter. Besides, it is possible to realize that values of attached materials on the inner surface of the main pipe of the equipment from 5% to around 30% of water content respect to the amount of soil, are relatively low regardless the temperature in the laboratory and the kind of soil. Furthermore, the previous mentioned parameter from around 30% to 80% of water content respect to the soil mass generally increases suddenly regardless the temperature in the laboratory and the kind of soil.

Figure 70 shows the attached materials on the inner surface of the main pipe of the equipment, the figure in question shows the equipment performance when dealing with GUM-WS2, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Water content in the mixture to process was changed, following the procedure explained before. In Figure 70, blue line "G2T15S1. Attach", red line "G2T15S2. Attach", green line "G2T25S1. Attach", violet line "G2T25S2. Attach" represent the attached materials on the inner surface of the main pipe of the equipment when processing the GUM-WS2 with temperature 15°C and soil 1, temperature 15°C and soil 2, temperature 25°C and soil 1, temperature 25°C and soil 2 respectively.

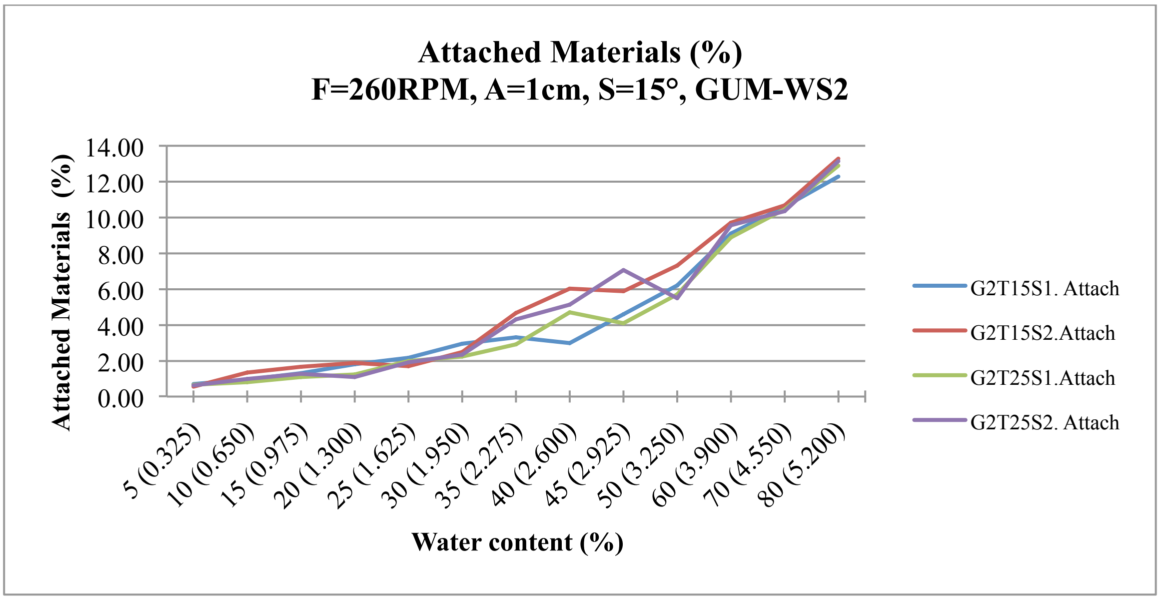

Fig. 70 Relationship between Attached Materials and Water Content (F=260RPM, A=1cm, S=15 and GUM-WS2)

After analyzing the experimental results shown in Figure 70, it is possible to notice that the attached materials on the inner surface of the main pipe of the equipment from 5% to 80% of water content respect to the amount of soil has a tendency of increasing while increasing the water content in the material to process, regardless of the temperature in the laboratory and the kind of soil. This fact proves, water content has a great influence on the previous mentioned parameter. Besides, it is possible to realize that values of attached materials on the inner surface of the main pipe of the equipment from 5% to around 30% of water content respect to the amount of soil, are relatively low regardless the temperature in the laboratory and the kind of soil. Furthermore, the previous mentioned parameter from around 30% to 80% of water content respect to the soil mass generally increases suddenly regardless the temperature in the laboratory and the kind of soil

4.4.4 Statistical analysis of rate of suction.

To carry out a statistical analysis of previous data, first it is necessary to know if they have normal distribution or non-normal distribution. There are significant amount of normality tests available in the literature. However, the most common normality test procedures available in statistical software are the Shapiro-Wilk test, Kolmogorov-Smirnov test, Anderson-Darling test and Lilliefors test. Among the four test mentioned, Shapiro-Wilk is the most powerful test for all types of distribution and sample sizes whereas Kolmogorov-Smirnov test is the least powerful test [44]. Therefore Shapiro-Wilk test (S-W) have been selected to analyze the normality condition of previous results related with rate of suction.

The Shapiro-Wilk test, calculates a W statistic that tests whether a random sample x_1, x_2, …, x_n comes from a normal distribution. The statistic is calculated as follow [45]:

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (7)$$

where the $x_{(i)}$ are the ordered sample values ($x_{(1)}$ is the smallest) and the a_i are constants generated from the means, variances and covariances of the order statistics of a sample of size n from a normal distribution [45]. Then, the alpha level (α) will be set at 0.05, it means that confidence level will be set at 95%.

- Null hypothesis (H_0) : the sample data are not significantly different from a normal distribution.
- Alternative hypothesis (H_a): the sample data are significantly different from a normal distribution.

To carry out the Shapiro-Wilk test, it will be used the software RStudio version 0.99.887. From this software is possible to obtain the value of W and p-value. If p-value is more than alpha level (0.05), it is possible to be 95% certain that the data are normally distributed, in other words, it is possible assume that H_0 is true. If p-value is less than alpha level (0.05), it is possible to be 95% certain that the data are not normally distributed, in other words, it is possible assume that H_0 is false. A data set with a *p*-value of 0.05 rejects the null hypothesis that the data are normally distributed [46].

It is necessary to be aware that these four mentioned normality tests do not perform well for small sample size (30 and bellow), therefore the power of Shapiro-Wilk test is low for small sample size [44]. The sample size in this study is 13 for every set of experimental conditions, then taking into consideration this previous fact, it is necessary to increase it. From this situation, arise the necessity to obtain a numerical model, with the goal to generate rate of suctions of the equipment changing the water content by 0.065%, then it will be possible to obtain 76 values of apparatus performance for each set of experimental conditions.

Linear least squares regression is by far the most widely used modeling method. It is what most people mean when they say they have used "regression", "linear regression" or "least squares" to fit a model to their data. Not only is linear least squares regression the most widely used modeling method, but it has been adapted to a broad range of situations that are outside its direct scope [45].

Used directly, with an appropriate data set, linear least squares regression can be used to fit the data with any function of the form [45]:

$$f(\vec{x}\,;\,\vec{\beta}) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \quad (8)$$

where the explanatory variable or "$\vec{x}$" in the function is multiplied by an unknown parameter "$\vec{\beta}$", there is at most one unknown parameter with no corresponding explanatory variable, and all of the individual terms are summed to produce the final function value [45].

In statistical terms, any function that meets these criteria would be called a "linear function". The term "linear" is used, even though the function may not be a straight line, because if the unknown parameters are considered to be variables and the explanatory variables are considered to be known coefficients corresponding to those "variables", then the problem becomes a system of linear equations that can be solved for the values of the unknown parameters. As just mentioned above, linear models are not limited to being straight lines or planes, but include a fairly wide range of shapes. For example, a simple quadratic curve (polynomial regression). For example, a simple quadratic curve [45]:

$$f(x\,;\,\vec{\beta}) = \beta_0 + \beta_1 x + \beta_{11} x^2 \quad (9)$$

Classical linear regression has assumptions that are required to obtain good ordinary least square estimates (known as best linear unbiased estimators). In this model, it is assumed that 'continuous predictor variables and the outcome variable are linearly related (Assumption 1). Regression techniques are possible for both categorical and continuous outcome variables, but for linear regression, it is assumed that the 'outcome variable is continuous (Assumption 2). It is assumed that there is no random component to x, including no measurement error (Assumption 3). To reach the convenient linear form, it is assumed that random component or error term is equal 0. This is the assumption of zero mean error (conditional on x) (Assumption 4) [47]

Taking into consideration, the shape of the graph related with the rate of suction, it is easy to understand that the most convenient procedure to obtain the numerical model should be the polynomial regression. Using the software RStudio version 0.99.887 it was obtained a fitted polynomial curve for every group of data, with the goal to generate rate of suctions of the equipment changing the water content by 0.065%. Table 7 shows, the fitted curve equation, the correlation factor (R^2), the statistic (W) and the p-value related with rate of suction.

Table 7 Fitted curve equation, correlation factor (R), statistics (W), p-value related with rate of suction

Group of data	Fitted polynomial curve equation	Correlation factor (R^2)	Statistic (W)	P-value
G1T15S1	$RS=-0.08x^4+1.08x^3-4.44x^2+4.87x+3.90$	0.9917	0.8197	$3.242*10^{-8}$
G1T15S2	$RS=-0.09x^4+1.15x^3-4.78x^2+5.60x+3.13$	0.9898	0.8170	$2.702*10^{-8}$
G1T25S1	$RS=-0.11x^4+1.40x^3-5.84x^2+7.41x+2.34$	0.9900	0.8189	$3.074*10^{-8}$
G1T25S2	$RS=-0.05x^4+0.69x^3-2.86x^2+2.68x+4.38$	0.9866	0.8406	$1.412*10^{-7}$
G2T15S1	$RS=-0.07x^4+0.92x^3-3.85x^2+4.14x+3.98$	0.9940	0.8272	$5.416*10^{-8}$
G2T15S2	$RS=-0.06x^4+0.80x^3-3.27x^2+3.32x+3.68$	0.9988	0.8250	$4.654*10^{-8}$
G2T25S1	$RS=-0.04x^4+0.64x^3-2.85x^2+3.38x+3.19$	0.9889	0.8429	$1.669*10^{-7}$
G2T25S2	$RS=-0.04x^4+0.50x^3-2.11x^2+1.75x+4.26$	0.9846	0.8494	$2.709*10^{-7}$

From Table 7, it is possible to notice that there is a good correlation between the obtained fitted curve and the experimental data, because R^2 is almost equal to 1. This fact means, those fitted curves are proper tools to simulate the rate of suctions of the equipment with those experimental conditions, changing the water content. On the other hand, analyzing the data related with p-value, it is possible to realize that they are lower than 0.05, then each group of values is not normally distributed, so H_0 is false. Afterwards, to compare group of data each other, it is necessary a non-parametric procedure. It will be used the Wilcoxon Signed Rank Test, this procedure is the convenient one to compare two matched and not normally distributed samples, besides this procedure calculates a "V", this value corresponds to the sum of ranks assigned to the differences (between two groups) with positive sign [48]. Then, the alpha level (α) will be set at 0.05, it means that confidence level will be set at 95%. Besides, the null hypothesis and alternative hypothesis were defined as follow:

- Null hypothesis (H_0): there is no a median difference between the two sets of rate of suction.
- Alternative hypothesis (H_a): there is a median difference between the two sets of rate of suction.

In this case, if p-value is more than alpha level (0.05), it is possible to be 95% certain that there is no a median difference between the two sets of rate of suction, in other words, it is possible assume that H_0 is true. If p-value is equal or less than alpha level (0.05), it is possible to be 95% certain that there is a median difference between the two sets of rate of suction, in other words, it is possible assume that H_0 is false [49]. Table 8 shows, the V values and p-values related with the comparison between sets of rate of suction changing soil and keeping constant temperature and GUM.

Table 8 Comparison between sets of rate of suction (changing soil)

Parameters	Comparison between sets of rate of suction			
	GIT15S1 and G1T15S2	G1T25S1 and G1T25S2	G2T15S1 and G2T15S2	G2T25S1 and G2T25S2
V	2926	2419	2872	2272
P-value	$3.679*10^{-14}$	$7.538*10^{-8}$	$3.047*10^{-13}$	$2.841*10^{-5}$

Analyzing the p-values shown in Table 8, it is possible to conclude the following. All p-values shown in Table 8 are lower than 0.05, therefore, there is a median difference between every compared set of rate of suction, then, H_0 is rejected. When the p-values are lower than 0.05, while this parameter is closer to alpha level, the difference between the two compared sets of rate of suction decreases, and while this parameter is closer to zero, the difference between the two compared sets of rate of suction increases. Then, the highest difference in the equipment performance was obtained when G1T15S1 and G1T15S2 were compared and the lowest difference was obtained when G2T25S1 and G2T25S2 were compared. In the case of highest difference, it was obtained with GUM-WS1 (lower specific surface area and water absorption) and temperature 15°C (lower temperature). Therefore under the previous mentioned conditions, the soil contained in the material to process has more probability to adsorb the water, because the recycled asphalt aggregate has lower water absorption and the mixture to process has less probability to release water due to the temperature in the laboratory. In the case of lowest difference, it was obtained with GUM-WS2 (higher specific surface area and water absorption) and temperature 25°C (higher temperature). Therefore under the previous mentioned conditions, the soil contained in the material to process has less probability to adsorb the water, because the recycled asphalt aggregate has higher water absorption and the mixture to process has more probability to release water due to the temperature in the laboratory. Then, there is a high probability, in the case of highest difference in equipment performance that, soil contained in the mixture to process has higher water content. This fact proves, the influence of soil water content in the equipment performance.

Table 9 shows, the V values and p-values related with the comparison between sets of rate of suction changing temperature and keeping constant soil and GUM.

Table 9 Comparison between sets of rate of suction (changing temperature)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G1T25S1	G2T15S1 and G2T25S1	G1T15S2 and G1T25S2	G2T15S2 and G2T25S2
V	773	1792	654	767
P-value	$3.573*10^{-4}$	0.089	$2.841*10^{-5}$	$3.172*10^{-4}$

From the analyses of the V values and p-values shown in Table 9, it is possible to conclude that one p-value (0.089) is higher than 0.05, therefore, there is no a median difference when compare G2T15S1 and G2T25S1, it is possible to assume that H_0 is true. On the other hand, the other three p-values are lower than 0.05, it means, there is a median difference between both compared sets of rate of suction, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the equipment performance was obtained when G1T15S2 and G1T25S2 were compared. In the case of highest difference, it was obtained with GUM-WS1 (lower specific surface area and water absorption) and soil 2 (higher clay percent). Clay-sized particles (<2μm) are responsible for most chemical reactions in soils [50]. The high reactivity of clay particles results from their much greater specific surface area than sand and silt particles and because the secondary mineral species that comprise the clay fraction often have high surface charge [50]. The research consider that, those previous clay properties cause a higher effect on equipment performance in the case of soil 2 than in the case of soil 1, because the former has higher clay percent in its composition. Besides, there is no median difference when compare G2T15S1 and G2T25S1, because those mixtures are composed by GUM-WS2 (higher specific surface area and water absorption) and soil 1 (lower clay percent), then changing temperature in those cases did not cause a great difference in the equipment performance.

Table 10 shows, the V values and p-values related with the comparison between sets of rate of suction changing GUM and keeping constant soil and temperature.

Table 10 Comparison between sets of rate of suction (changing GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T15S1	G1T25S1 and G2T25S1	G1T15S2 and G2T15S2	G1T25S2 and G2T25S2
V	2725	2588	2235	2925
P-value	$6.523*10^{-11}$	$5.817*10^{-9}$	$6.488*10^{-5}$	$3.828*10^{-14}$

Table 10 shows the results related with the comparison between sets of rate of suction changing only GUM. From those results, it is possible to conclude that all p-values are lower than 0.05, it means, there is a median difference between both compared sets of rate of suction, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the equipment performance was obtained when G1T25S2 and G2T25S2 were compared and the lowest difference was obtained when G1T15S2 and G2T15S2 were compared. In the case of highest difference, it was obtained with temperature 25°C (higher temperature) and soil 2 (higher clay percent), in this case it is believed that changing GUM-WS, changes the water absorbed by the soil in the mixture, and that difference in soil moisture content in the case of soil 2 (higher clay percent) can produce a higher effect on equipment performance. In the case of lower difference (comparison between G1T15S2 and G2T15S2), it was also obtain with soil 2 (higher clay percent) but with temperature 15°C (lower temperature), this results prove that many factors can affect the equipment performance because even the soil 2 has higher clay percent in its composition, it is possible to obtain similar rate of suction of the equipment when change the characteristics of GUM-WS to process.

Table 11 shows, the V values and p-values related with the comparison between sets of rate of suction changing soil and temperature, keeping constant GUM.

Table 11 Comparison between sets of rate of suction (changing soil and temperature)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G1T25S2	G2T15S1 and G2T25S2	G1T25S1 and G1T15S2	G2T25S1 and G2T15S2
V	1998	2282	2831	2220
P-value	$5.652*10^{-3}$	$2.259*10^{-5}$	$1.441*10^{-12}$	$8.978*10^{-5}$

Analyzing the V values and p-values shown in Table 11, it is possible to conclude the following. All p-values shown in Table 11 are lower than 0.05, therefore, there is a median difference between every compared set of rate of suction, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the equipment performance was obtained when G1T25S1 and G1T15S2 were compared and the lowest difference was obtained when G1T15S1 and G1T25S2 were compared. In the case of highest difference, it was obtained with GUM-WS1 (lower specific surface area and water absorption), it is interesting to notice that, in the case of comparison changing only soil and only temperature the highest differences were obtained in both cases with GUM-WS1. Besides, in the case of lowest difference, this time (changing soil and temperature) was obtained with GUM-WS1 too, but in previous comparisons (changing only soil and only temperature), the lowest differences were obtained with GUM-WS2. This fact proves, rate of suction of the equipment is influenced by many factors at the same time.

Table 12 shows, the V values and p-values related with the comparison between sets of rate of suction changing temperature and GUM, keeping constant the soil.

Table 12 Comparison between sets of rate of suction (changing temperature and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T25S1	G1T25S1 and G2T15S1	G1T15S2 and G2T25S2	G1T25S2 and G2T15S2
V	1918	2453	2525	2926
P-value	0.0186	$3.007*10^{-7}$	$3.89*10^{-8}$	$3.679*10^{-14}$

From the analysis of V values and p-values shown in Table 12, it is possible to conclude the following. All p-values shown in Table 12 are lower than 0.05, therefore, there is a median difference between every compared set of rate of suction, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the equipment performance was obtained when G1T25S2 and G2T15S2 were compared and the lowest difference was obtained when G1T15S1 and G2T25S1 were compared. In the case of highest difference, it was obtained with soil 2 (higher clay percent), it is interesting to comment, in the case of comparison changing only temperature and only GUM the highest differences were obtained with soil 2 in both cases. Besides, in the case of lowest difference, this time (changing temperature and

GUM) was obtained with soil 1 (lower clay percent), further in previous comparisons, changing only temperature and only GUM, the lowest differences were obtained with soil 1 in the case of former comparison and with soil 2, in the case of latter comparison. This fact proves, rate of suction of the equipment is influenced by many factors at the same time.

Table 13 shows, the V values and p-values related with the comparison between sets of rate of suction changing soil and GUM, keeping constant the temperature.

Table 13 Comparison between sets of rate of suction (changing soil and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T15S2	G1T25S1 and G2T25S2	G2T15S1 and G1T15S2	G2T25S1 and G1T25S2
V	2926	2817	2905	1125
P-value	$3.697*10^{-14}$	$2.425*10^{-12}$	$8.448*10^{-14}$	0.0806

From the analyses of the V values and p-values shown in Table 13, it is possible to conclude that one p-value (0.0806) is higher than 0.05, therefore, there is no a median difference when compare G2T25S1 and G1T25S2, it is possible to assume that H_0 is true. On the other hand, the other three p-values are lower than 0.05, it means, there is a median difference between both compared sets of rate of suction, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference was obtained when G1T15S1 and G2T15S2 were compared. In the case of highest difference, it was obtained with temperature 15°C (lower temperature), it is interesting to notice that, in the case of comparison changing only soil and only GUM the highest differences was obtained with 15°C in the case of former comparison but in the case of latter comparison it was obtained with 25°C. Besides, in the case of lowest difference changing soil and GUM (lowest difference is considered zero) was obtained with temperature 25°C, but in previous comparisons, changing only soil and only GUM, the lowest differences were obtained with 25°C in the case of former comparison and in the case of latter comparison it was obtained with 15°C. This fact proves, rate of suction of the equipment is influenced by many factors at the same time.

Table 14 shows, the V values and p-values related with the comparison between sets of rate of suction changing soil, temperature and GUM at the same time.

Table 14 Comparison between sets of rate of suction (changing soil, temperature and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T25S2	G1T25S1 and G2T15S2	G2T25S1 and G1T15S2	G2T15S1 and G1T25S2
V	2525	2897	1379	1654
P-value	$3.890*10^{-8}$	$1.156*10^{-13}$	0.6655	0.324

From the analyses of the V values and p-values shown in Table 14, it is possible to conclude that two p-values (0.6655 and 0.324) are higher than 0.05, therefore, there is no a median difference when compare G2T25S1 with G1T15S2 and G2T15S1 with G1T25S2 respectively, it is possible to assume that H_0 is true. On the other hand, the other two p-values are lower than 0.05, it means, there is a median difference between both compared sets of rate of suction, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference was obtained when G1T25S1 and G2T15S2 were compared. Besides, when p-values are higher than 0.05, while this parameter is closer to alpha level, even the two compared sets of data are similar, the difference between them increases, and while this parameter is farther from alpha level, even the two compared sets of data are similar the difference decreases. Therefore, the most similar couple of data, changing soil, temperature and GUM is G2T25S1 and G1T15S2.

Table 15 shows, the V values and p-values related with the comparisons with highest difference under each set of experimental conditions.

Table 15 Comparison with highest difference under each set of experimental conditions

Parameters	Comparison with highest difference for each set of conditions						
	Changing soil (G1T15S1 and G1T15S2)	Changing temperature (G1T15S2 and G1T25S2)	Changing GUM (G1T25S2 and G2T25S2)	Changing soil and temperature (G1T25S1 and G1T15S2)	Changing temperature and GUM (G1T25S2 and G2T15S2)	Changing soil and GUM (G1T15S1 and G2T15S2)	Changing soil, temperature and GUM G1T25S1 and G2T15S2
V	2926	654	2925	2831	2926	2926	2897
P-value	$3.68*10^{-14}$	$2.84*10^{-5}$	$3.83*10^{-14}$	$1.44*10^{-12}$	$3.68*10^{-14}$	$3.70*10^{-14}$	$1.156*10^{-13}$

Analyzing the p-values shown in Table 15, it is possible to conclude the following. The two highest differences in equipment performance, taking into consideration all kind of comparisons, were obtained when compare G1T15S1 with G1T15S2 and G1T25S2 with G2T15S2. The former comparison was changing only the soil and the latter was changing temperature and GUM. This fact proves, it is not necessary change all considered factors that influence on equipment performance to obtain a bigger effect on rate of suction of the apparatus, then, changing only one factor can has a great influence on equipment performance, in this case, changing only the soil.

Table 16 shows, the V values and p-values related with the comparisons with lowest difference in each set of conditions or similar couple of data.

Table 16 Comparison with lowest difference in each set of conditions or similar couple of data

Parameters	Comparison with lowest difference in each set of conditions						
	Changing soil (G2T25S1 and G2T25S2)	Changing temperature (G2T15S1 and G2T25S1)	Changing GUM (G1T15S2 and G2T15S2)	Changing soil and temperature (G1T15S1 and G1T25S2)	Changing temperature and GUM (G1T15S1 and G2T25S1)	Changing soil and GUM (G2T25S1 and G1T25S2)	Changing soil, temperature and GUM (G2T25S1 and G1T15S2)
V	2272	1792	2235	1998	1918	1125	1379
P-value	$2.841*10^{-5}$	0.089	$6.488*10^{-5}$	$5.652*10^{-3}$	0.0186	0.0806	0.6655

Analyzing the V values and p-values shown in Table 16, it is possible to conclude the following. The two most similar data, taking into consideration all kind of comparisons, were found when G2T25S1 with G1T15S2 were compared. It is very interesting to notice, in previous mentioned comparison, GUM, temperature and soil were changed, even though those changes, they did not affect the rate of suction of the apparatus. This fact proves, changing all parameters, do not means a great affect on equipment performance.

Table 17 shows, the means of V values and means of p-values related with each type of comparisons.

Table 17 Means of V values and p-values related with each type of comparison

Parameters	Comparison with lowest difference in each set of conditions						
	changing soil	changing temperature	changing GUM	changing soil and temperature	changing temperature and GUM	changing soil and GUM	changing soil, temperature and GUM
Mean (V)	2622.25	996.5	2618.25	2332.75	2455.5	2443.25	2113.75
Mean (P-value)	$7.291*10^{-7}$	0.022	$1.622*10^{-5}$	$1.441*10^{-3}$	$4.655*10^{-3}$	0.020	0.247

From the analysis of p-values shown in Table 17, it is possible to conclude that, changing only the soil in the material to process was the variation, that most affect the equipment performance, at least with those experimental conditions and those used materials in the experiment. On the other hand, changing soil, temperature and GUM were the changes that less affect the rate of suction of the apparatus. At least, with those used materials and conditions in the experiments.

4.4.5 Statistical analysis of recovery.

Shapiro-Wilk test (S-W) have been selected to analyze the normality condition of experimental results related with recovery, then the formula number (4) will be used to calculate the "W statistics" in this section, the same formula used in section "*4.4.4 Statistical analysis of rate of suction.*". The alpha level (α) and confidence level will be set at 0.05 and 95%, respectively, the same values used in section "*4.4.4 Statistical analysis of rate of suction.*". Besides, the null hypothesis and alternative hypothesis were defined as follow:

- Null hypothesis (H_0) : the sample data are not significantly different from a normal distribution.
- Alternative hypothesis (H_a): the sample data are significantly different from a normal distribution.

To carry out the Shapiro-Wilk test, it will be used the same software RStudio version 0.99.887. From this software is possible to obtain the value of W and p-value. If p-value is more than alpha level (0.05), it is possible to be 95% certain that the data are normally distributed, in other words, it is possible assume that H_0 is true. If p-value is less than or equal to alpha level (0.05), it is possible to be 95% certain that the data are not normally distributed, in other words, it is possible assume that H_0 is false.

As mentioned before, the power of Shapiro-Wilk test is low for small sample size (30 and bellow), [44]. The sample size in this study is 13 for every set of experimental conditions, then taking into consideration this previous fact, it is necessary to increase it. Using the software RStudio version 0.99.887 it was obtained a fitted polynomial curve for every group of data, with the goal to generate recoveries of the equipment changing the water content by 0.065%. Table 18 shows, the fitted polynomial curve equation, the correlation factor (R^2), the statistic (W) and the p-value related with recovery.

Table 18 Fitted curve equation, correlation factor (R), statistics (W), p-value related with recovery

Group of data	Fitted curve equation	Correlation factor (R^2)	Statistic (W)	P-value
G1T15S1	$Rec=-0.08x^{10}+2.24x^9-25.67x^8+165.32x^7-656.42x^6+1665.36x^5-2711.1x^4+2774.27x^3-1694.66x^2+550.67x+15.12$	0.96	0.9455	$2.639*10^{-3}$
G1T15S2	$Rec=0.06x^{10}-1.63x^9+18.36x^8-117.8x^7+475.1x^6-1252x^5+2162x^4-2387x^3+1581x^2-554.4x+160.4$	0.94	0.5682	$1.31*10^{-13}$
G1T25S1	$Rec=0.02x^{10}-0.78x^9+11.62x^8-93.49x^7+453.4x^6-1384x^5+2673x^4-3188x^3+2205x^2-780.5x+191.3$	0.96	0.7557	$6.473*10^{-10}$
G1T25S2	$Rec=0.29x^{10}-7.37x^9+82.21x^8-518.9x^7+2041.51x^6-5194.06x^5+8573.24x^4-8952.89x^3+5571.16x^2-1829.73x+317.37$	0.96	0.5127	$1.77*10^{-14}$
G2T15S1	$Rec=-0.11x^{10}+2.84x^9-32.32x^8+208.58x^7-838.91x^6+2178.27x^5-3656.14x^4+3859.34x^3-2405.35x^2+780.5x-13.78$	0.95	0.5973	$4.023*10^{-13}$
G2T15S2	$Rec=-0.05x^{10}+1.25x^9-12.35x^8+65.91x^7-204.65x^6+363.29x^5-314.86x^4+16.93x^3+180.1x^2-112.23x+102.69$	0.91	0.6807	$1.433*10^{-11}$
G2T25S1	$Rec=-0.11x^{10}+2.87x^9-31.92x^8+200.83x^7-787.07x^6+1994.80x^5-3286.35x^4+3445x^3-2174.85x^2+732.89x-11.13$	0.93	0.5674	$1.269*10^{-13}$
G2T25S2	$Rec=-0.13x^{10}+3.29x^9-35.34x^8+213.5x^7-799.4x^6+1923x^5-2983x^4+2913x^3-1693x^2+523x-18.77$	0.98	0.5110	$1.671*10^{-14}$

From Table 18, it is possible to notice that there is a good correlation between the obtained fitted polynomial curve and the experimental data, because correlation factor (R^2) is almost equal to 1. It means, those fitted curves are proper tools to simulate the recovery of the equipment with those experimental conditions, changing water content. On the other hand, analyzing the data related with p-value, it is possible to realize that all of them are lower than 0.05, then each group of values is not normally distributed, then H_0 is false. Afterwards, to compare group of data each other, it is necessary a non-parametric procedure. It will be used the Wilcoxon Signed Rank Test, this procedure is the convenient one to compare two matched and not normally distributed samples, besides this procedure calculates a "V", this value corresponds to the sum of ranks assigned to the differences (between two groups) with positive sign [48]. Then, the alpha level (α) will be set at 0.05, it means that confidence level will be set at 95%. Besides, the null hypothesis and alternative hypothesis were defined as follow:

- Null hypothesis (H_0): there is no a median difference between two sets of recovery.
- Alternative hypothesis (H_a): there is a median difference between two sets of recovery.

In this case, if p-value is bigger than alpha level (0.05), it is possible to be 95% certain that there is no a median difference between the two sets of recovery, in other words, it is possible assume that H_0 is true. If p-value is less than or equal to alpha level (0.05), it is possible to be 95% certain that there is a median difference between the two sets of recovery, in other words, it is possible assume that H_0 is false. Table 19 shows, the V values and p-values related with the comparison between sets of recovery changing soil and keeping constant temperature and GUM.

Table 19 Comparison between sets of recovery (changing soil)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G1T15S2	G1T25S1 and G1T25S2	G2T15S1 and G2T15S2	G2T25S1 and G2T25S2
V	2777	2464	1106	2288
P-value	$1.043*10^{-11}$	$2.22*10^{-7}$	0.0649	$1.966*10^{-5}$

Analyzing the p-values shown in Table 19, it is possible to conclude the following. When compare G2T15S1 and G2T15S2 the p-value is bigger than alpha level (0.05), it means there is no median difference between those two sets of recovery, therefore, H_0 is true. The other three p-values shown in Table 19 are lower than 0.05, therefore, there is a median difference between every compared set of recovery, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. So, the highest difference in the recovery was obtained when G1T15S1 and G1T15S2 were compared and it was obtained with GUM-WS1 (lower specific surface area and water absorption) and temperature 15°C (lower temperature). It means changing soil with those experimental conditions, causes a bigger influence on the recovery. On the other hand, G2T15S1 and G2T15S2 are similar, as mentioned before, it means, changing soil with GUM-

WS2 (higher specific surface area and water absorption) and temperature 15°C (lower temperature) do not cause variability on the recovery.

Table 20 shows, the V values and p-values related with the comparison between sets of recovery changing temperature and keeping constant soil and GUM.

Table 20 Comparison between sets of recovery (changing temperature)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G1T25S1	G2T15S1 and G2T25S1	G1T15S2 and G1T25S2	G2T15S2 and G2T25S2
V	973	695	2288	1838
P-value	0.0113	$7.079*10^{-5}$	$1.966*10^{-5}$	0.0525

From the analysis of the p-values shown in Table 20, it is possible to conclude the following. When compare G2T15S2 and G2T25S2 the p-value is bigger than alpha level (0.05), it means there is no median difference between those two sets of recovery, therefore, H_0 can be accepted. The other three p-values shown in Table 20 are lower than 0.05, therefore, there is a median difference between every compared set of recovery, then, H_0 is rejected. When the p-values are lower than 0.05, while this parameter is closer to alpha level, the difference between the two compared sets of recovery decreases, and while this parameter is closer to zero, the difference between the two compared sets of recovery increases. Then, the highest difference in the recovery was obtained when G1T15S2 and G1T25S2 were compared and it was obtained with GUM-WS1 (lower specific surface area and water absorption) and soil 2 (higher clay percent). It means changing temperature with those experimental conditions, causes a bigger influence on the recovery. On the other hand, there is no median difference between G2T15S2 and G2T25S2, it means, changing temperature with GUM-WS2 (higher specific surface area and water absorption) and soil 2 (higher clay percent) do not cause variability on the recovery.

Table 21 shows, the V values and p-values related with the comparison between sets of recovery changing GUM and keeping constant soil and temperature.

Table 21 Comparison between sets of recovery (changing GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T15S1	G1T25S1 and G2T25S1	G1T15S2 and G2T15S2	G1T25S2 and G2T25S2
V	1669	1715	681	779
P-value	0.2874	0.1929	$5.208*10^{-5}$	$4.021*10^{-4}$

From the analysis of the p-values shown in Table 21, it is possible to conclude the following. When compare G1T15S1 with G2T15S1 and G1T25S1 with G2T25S1 the p-values are bigger than alpha level (0.05), it means there is no median difference between those sets of recovery, therefore, H_0 is true. The other two p-values shown in Table 21 are lower than 0.05, therefore, there is a median difference between every compared set of recovery, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the recovery was obtained when G1T15S2 and G2T15S2 were compared and it was obtained with temperature 15°C (lower temperature) and soil 2 (higher clay percent). It means changing GUM with those experimental conditions, causes a bigger influence on the recovery. On the other hand, when the p-value is higher than 0.05, it was explained what happen when it closer to 0.05 and when is farther from 0.05. Therefore, the most similar recoveries were obtained when compare G1T15S1 with G2T15S1, it means, changing GUM with temperature 15°C (lower temperature) and soil 1 (lower clay percent) cause lower variability on the recovery.

Table 22 shows, the V values and p-values related with the comparison between sets of recovery changing constant soil and temperature, keeping constant GUM.

Table 22 Comparison between sets of recovery (changing soil and temperature)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G1T25S2	G2T15S1 and G2T25S2	G1T25S1 and G1T15S2	G2T25S1 and G2T15S2
V	2578	1808	2517	1854
P-value	$7.92*10^{-9}$	0.0745	$4.915*10^{-8}$	0.0432

Analyzing the p-values shown in Table 22, it is possible to conclude the following. When compare G2T15S1 and G2T25S2 the p-value is bigger than alpha level (0.05), it means there is no median difference between those two sets of recovery, therefore, H_0 is true. The other three p-values shown in Table 22 are lower than 0.05, therefore, there is a median difference between every compared set of recovery, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the recovery was obtained when G1T15S1 and G1T25S2 were compared and it was obtained with GUM-WS1 (lower specific surface area and water absorption). It means changing temperature and soil with those experimental conditions, cause a bigger influence on the recovery. On the other hand, as mentioned before G2T15S1 and G2T25S2 are similar, it means, changing temperature and soil with GUM-WS2 (higher specific surface area and water absorption) do not cause variability on the recovery.

Table 23 shows, the V values and p-values related with the comparison between sets of recovery changing temperature and GUM, keeping constant the soil.

Table 23 Comparison between sets of recovery (changing temperature and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T25S1	G1T25S1 and G2T15S1	G1T15S2 and G2T25S2	G1T25S2 and G2T15S2
V	1014	2069	1372	589
P-value	0.0202	$1.719*10^{-3}$	0.6394	$6.114*10^{-6}$

Analyzing the p-values shown in Table 23, it is possible to conclude the following. When compare G1T15S2 and G2T25S2 the p-value is bigger than alpha level (0.05), it means there is no median difference between those two sets of recovery, therefore, H_0 is true. The other three p-values shown in Table 23 are lower than 0.05, therefore, there is a median difference between every compared set of recovery, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the recovery was obtained when G1T25S2 and G2T15S2 were compared and it was obtained with soil 2 (higher clay percent). It means changing GUM and temperature with those experimental conditions, cause a bigger influence on the recovery. On the other hand, as mentioned before G1T15S2 and G2T25S2 are similar, it means, changing temperature and GUM with soil 2 (higher clay percent) do not cause variability on the recovery. It is interesting to notice, highest difference and similar recoveries were obtained with the same kind of soil. Therefore, it is believed there is at least one more factor that influence on recovery.

Table 24 shows, the V values and p-values related with the comparison between sets of recovery changing soil and GUM, keeping constant the temperature.

Table 24 Comparison between sets of recovery (changing soil and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T15S2	G1T25S1 and G2T25S2	G2T15S1 and G1T15S2	G2T25S1 and G1T25S2
V	1279	2232	1905	2428
P-value	0.3421	$6.927*10^{-5}$	0.0223	$5.928*10^{-7}$

Examining the p-values shown in Table 24, it is possible to conclude the following. When compare G1T15S1 and G2T15S2 the p-value is bigger than alpha level (0.05), it means there is no median difference between those two sets of recovery, therefore, H_0 is true. The other three p-values shown in Table 24 are lower than 0.05, therefore, there is a median difference between every compared set of recovery, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the recovery was obtained when G2T25S1 and G1T25S2 were compared and it was obtained with temperature 25°C (higher temperature). It means changing soil and GUM with those experimental conditions, cause a bigger influence on the recovery. On the other hand, there is no median difference between G1T15S1 and G2T15S2, it means, changing GUM and soil with temperature 15°C (lower temperature) do not cause variability on the recovery.

Table 25 shows, the V values and p-values related with the comparison between sets of recovery changing soil, temperature and GUM at the same time.

Table 25 Comparison between sets of recovery (changing soil, temperature and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T25S2	G1T25S1 and G2T15S2	G2T25S1 and G1T15S2	G2T15S1 and G1T25S2
V	1879	1648	2445	2246
P-value	0.0315	0.3395	$3.743*10^{-7}$	$5.094*10^{-5}$

Examining the p-values shown in Table 25, it is possible to conclude the following. When compare G1T25S1 and G2T15S2 the p-value is bigger than alpha level (0.05), it means there is no median difference between those two sets of recovery, therefore, H_0 is true. The other three p-values shown in Table 25 are lower than 0.05, therefore, there is a median difference between every compared set of recovery, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the recovery was obtained when G2T25S1 and G1T15S2 were compared. It is possible obtain similar recoveries or difference recoveries when change soil, temperature and GUM at the same time, as it is shown in Table 25. This fact means, there is at least one more factor influence on recovery or the considered factors have opposite influence on recovery under some specific conditions.

Table 26 shows, the V values and p-values related with the comparisons with highest difference under each set of experimental conditions.

Table 26 Comparison with highest difference under each set of experimental conditions

Parameters	Comparison with highest difference in each set of conditions						
	Changing soil (G1T15S1 and G1T15S2)	Changing temperature (G1T15S2 and G1T25S2)	changing GUM (G1T15S2 and G2T15S2)	changing soil and temperature (G1T15S1 and G1T25S2)	changing temperature and GUM (G1T25S2 and G2T15S2)	changing soil and GUM (G2T25S1 and G1T25S2)	changing soil, temperature and GUM G2T25S1 and G1T15S2
V	2777	2288	681	2578	589	2428	2445
P-value	$1.043*10^{-11}$	$1.966*10^{-5}$	$5.208*10^{-5}$	$7.92*10^{-9}$	$6.114*10^{-6}$	$5.928*10^{-7}$	$3.743*10^{-7}$

Analyzing the p-values shown in Table 26, it is possible to conclude the following. The highest effect on recovery, taking into consideration all kind of comparisons, was found when compare G1T15S1 with G1T15S2. It is very interesting to notice, this comparison was changing only the soil. This fact proves, it is not necessary change all parameters that influence on recovery to obtain a great difference in the mentioned parameter, then, changing only one factor can has a great influence on equipment performance, at least with those used experimental materials.

Table 27 shows, the V values and p-values related with the comparisons with lowest difference or more similar couple of data under each set of experimental conditions.

Table 27 Comparison with lowest difference or similar couple of data under each set of experimental conditions

Parameters	Comparison with lowest difference in each set of conditions						
	changing soil G2T15S1 and G2T15S2	changing temperature G2T15S2 and G2T25S2	changing GUM G1T15S1 and G2T15S1	changing soil and temperature G2T15S1 and G2T25S2	changing temperature and GUM G1T15S2 and G2T25S2	changing soil and GUM G1T15S1 and G2T15S2	changing soil, temperature and GUM G1T25S1 and G2T15S2
V	1106	1838	1669	1808	1372	1279	1648
P-value	0.0649	0.0525	0.2874	0.0745	0.6394	0.3421	0.3395

Examining the p-values shown in Table 27, it is possible to conclude the following. The two most similar data, taking into consideration all kind of comparisons, were found when compare G1T15S2 with G2T25S2. It is very interesting to notice, in previous mentioned comparison, GUM and temperature were changed, even though those changes, they did not affect the recovery. This fact proves, changing factors, do not means a variation on recovery.

Table 28 shows, the means of V values and means of p-values related with each type of comparisons.

Table 28 Means of V values and p-values related with each type of comparisons

Parameters	Comparison with lowest difference in each set of conditions						
	changing soil	changing temperature	changing GUM	changing soil and temperature	changing temperature and GUM	changing soil and GUM	changing soil, temperature and GUM
Mean (V)	2158.75	1448.5	1211	2189.25	1261	1961	2054.5
Mean (P-value)	0.0162	0.0160	0.1292	0.0294	0.1653	0.0911	0.0928

From the analysis of p-values shown in Table 28, it is possible to conclude that, changing only the temperature in the material to process was the fact, that most affect the recovery, at least with those experimental conditions and those used materials in the experiment. It is interesting to notice that, changing only the soil had almost the same effect on recovery, comparing with the effect of temperature. On the other hand, changing temperature and GUM were the changes that less affect the recovery of GUM. At least, with those used materials and conditions in the experiments.

4.4.6 Statistical analysis of attached materials.

Shapiro-Wilk test (S-W) have been selected to analyze the normality condition of experimental results related with attached materials on the inner surface of the main pipe of the equipment, then the formula number (4) will be used to calculate the "W statistics" in this section, the same formula used in section "*4.4.4 Statistical analysis of rate of suction.*". The alpha level (α) and confidence level will be set at 0.05 and 95%, respectively, the same values used in section "*4.4.4 Statistical analysis of rate of suction.*". Besides, the null hypothesis and alternative hypothesis were defined as follow:

- Null hypothesis (H_0) : the sample data are not significantly different from a normal distribution.
- Alternative hypothesis (H_a): the sample data are significantly different from a normal distribution.

To carry out the Shapiro-Wilk test, it will be used the same software RStudio version 0.99.887. From this software is possible to obtain the value of W and p-value. If p-value is more than alpha level (0.05), it is possible to be 95% certain that the data are normally distributed, in other words, it is possible assume that H_0 is true. If p-value is less than or equal to alpha level (0.05), it is possible to be 95% certain that the data are not normally distributed, in other words, it is possible assume that H_0 is false.

As mentioned before, the power of Shapiro-Wilk test is low for small sample size (30 and bellow) [44]. As mentioned before, the sample size in this study is 13 for every set of experimental conditions, then taking into consideration this previous fact, it is necessary to increase it. Using the software RStudio version 0.99.887 it was obtained a fitted polynomial curve for every group of data, with the goal to generate attached materials on the inner surface of the main pipe of the equipment changing the water content by 0.065%. Table 29 shows, the fitted polynomial curve equation, the correlation factor (R^2), the statistic (W) and the p-value related with the attached materials.

Table 29 Fitted curve equation, correlated factor (R), statistics (W), p-value related with attached materials

Group of data	Fitted polynomial curve equation	Correlation factor (R^2)	Statistic (W)	P-value
G1T15S1	$Att=0.003x^4-0.07x^3+0.84x^2-0.58x+0.93$	0.9817	0.9088	$4.523*10^{-5}$
G1T15S2	$Att=-0.16x^4+1.71x^3-5.12x^2+6.22x-1.13$	0.9391	0.8434	$1.724*10^{-7}$
G1T25S1	$Att=-0.15x^4+1.57x^3-4.45x^2+4.91x-0.76$	0.9684	0.8279	$5.695*10^{-8}$
G1T25S2	$Att=0.1x^4-1.29x^3+5.77x^2-7.15x+2.88$	0.9545	0.9102	$5.181*10^{-5}$
G2T15S1	$Att=-0.09x^4+0.92x^3-2.49x^2+3.48x-0.33$	0.9908	0.8882	$6.496*10^{-6}$
G2T15S2	$Att=0.03x^4-0.46x^3+2.40x^2-2.20x+1.44$	0.9841	0.9212	$1.614*10^{-4}$
G2T25S1	$Att=-0.03x^4+0.28x^3-0.25x^2+0.64x+0.45$	0.9906	0.8990	$1.748*10^{-5}$
G2T25S2	$RS=0.05x^4+0.69x^3+3.22x^2-3.37x+1.67$	0.9750	0.9227	$1.911*10^{-4}$

From Table 29, it is possible to notice that there is a good correlation between the obtained fitted polynomial curve and the experimental data, because R^2 is almost equal to 1. This fact means, those fitted polynomial curves are proper tools to simulate the attached materials of the equipment with those experimental conditions, changing the water content. On the other hand, analyzing the data related with p-value, it is possible to realize that they are lower than 0.05, then each group of values is not normally distributed, then H_0 is false. Afterwards, to compare group of data each other, it is necessary a non-parametric procedure. It will be used, the same method, Wilcoxon Signed Rank Test, this procedure is the convenient one to compare two matched and not normally distributed samples, besides this procedure calculates a "V", this value corresponds to the sum of ranks assigned to the differences (between two groups) with positive sign [48]. Then, the alpha level (α) will be set at 0.05, it means that confidence level will be set at 95%. Besides, the null hypothesis and alternative hypothesis were defined as follow:

- Null hypothesis (H_0): there is no a median difference between two sets of attached materials.
- Alternative hypothesis (H_a): there is a median difference between two sets of attached materials.

In this case, if p-value is more than alpha level (0.05), it is possible to be 95% certain that there is no a median difference between the two sets of attached materials, in other words, it is possible assume that H_0 is true. If p-value is less than or equal to alpha level (0.05), it is possible to be 95% certain that there is a median difference between the two sets of attached materials, in other words, it is possible assume that H_0 is false. Table 30 shows, the V values and p-values related with the comparison between sets of attached materials changing soil and keeping constant temperature and GUM.

Table 30 Comparison between sets of attached materials (changing soil)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G1T15S2	G1T25S1 and G1T25S2	G2T15S1 and G2T15S2	G2T25S1 and G2T25S2
V	1336	880	211	391
P-value	0.5125	$2.563*10^{-3}$	$9.205*10^{-11}$	$2.897*10^{-8}$

Analyzing the V values and p-values shown in Table 30, it is possible to conclude the following. When compare “G1T15S1 and G1T15S2” the p-value is higher than 0.05, then in this case, there is no median difference between those mentioned set of attached materials, it is possible assume that H_0 is true. On the other hand, in the case of the other three comparisons p-values are lower than 0.05, therefore, there is a median difference between every compared set of attached materials, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the attached materials was obtained when G2T15S1 and G2T15S2 were compared. This fact means, higher specific surface area and water absorption (GUM-WS2) with lower temperature (15°C) cause higher difference in attached materials, at least with the used samples and those experimental conditions. On the other hand, when compare G1T15S1 and G1T15S2 with lower specific surface area and water absorption (GUM-WS1) with lower temperature (15°C), there is no median difference between those mentioned attached materials, as mentioned before, therefore, in this case changing soil does not has a great influence on attached materials. It is interesting to notice that, GUM-WS is the only change between the comparison with highest difference in attached materials and that one with not median difference in attached materials. As a conclusion, it is possible to state, changing GUM (difference specific surface area and water absorption) has a great influence on attached materials.

Table 31 shows, the V values and p-values related with the comparison between sets of attached materials changing temperature and keeping constant soil and GUM.

Table 31 Comparison between sets of attached materials (changing temperature)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G1T25S1	G2T15S1 and G2T25S1	G1T15S2 and G1T25S2	G2T15S2 and G2T25S2
V	2000	2486	1168	2926
P-value	$5.475*10^{-3}$	$1.198*10^{-7}$	0.1273	$3.679*10^{-14}$

From the analysis of V values and p-values shown in Table 31, it is possible to conclude the following. When compare "G1T15S2 and G1T25S2" the p-value is higher than 0.05, then in this case, there is no median difference between those mentioned attached materials, it is possible assume that H_0 is true. On the other hand, in the case of the other three comparisons p-values are lower than 0.05, therefore, there is a median difference between every compared set of attached materials, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the attached materials was obtained when G2T15S2 and G2T25S2 were compared. This fact means, higher specific surface area and water absorption (GUM-WS2) with higher percentage of clay (S2) cause higher difference in attached materials, at least with the used samples and those experimental conditions. On the other hand, when compare G1T15S2 and G1T25S2 with lower specific surface area and water absorption (GUM-WS1) with higher percentage of clay (S2), there is no median difference between those mentioned attached materials, as mentioned before, therefore, in this case changing temperature does not has a great influence on attached materials. It is interesting to notice that, GUM-WS is the only change between the comparison with highest difference in attached materials and that one with not median difference in attached materials. As a conclusion, it is possible to state, changing GUM (difference specific surface area and water absorption) has a great influence on attached materials.

Table 32 shows, the V values and p-values related with the comparison between sets of attached materials changing GUM and keeping constant soil and temperature.

Table 32 Comparison between sets of attached materials (changing GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T15S1	G1T25S1 and G2T25S1	G1T15S2 and G2T15S2	G1T25S2 and G2T25S2
V	516	721	543	701
P-value	$9.566*10^{-7}$	$1.235*10^{-4}$	$1.93*10^{-6}$	$8.062*10^{-5}$

From the analysis of V values and p-values shown in Table 32, it is possible to conclude the following. All comparisons have p-values lower than 0.05, therefore, there is a median difference between every compared set of attached materials, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the attached materials was obtained when G1T15S1 and G2T15S1 were compared. This fact means, lower temperature (15°C) and lower percentage of clay (S1) cause higher difference in attached materials, at least with the used samples and those experimental conditions. On the other hand, the lowest difference in the attached materials was obtained when G1T25S1 and G2T25S1 were compared. This fact means, higher temperature (25°C) and lower percentage of clay (S1) cause lower difference in attached materials, at least with the used samples and those experimental conditions. In this group of comparisons, changing GUM, it is interesting to notice, all comparisons have median difference, this fact, confirm changing GUM (difference specific surface area and water absorption) have a great influence on attached materials.

Table 33 shows, the V values and p-values related with the comparison between sets of attached materials changing constant soil and temperature, keeping constant GUM.

Table 33 Comparison between sets of attached materials (changing soil and temperature)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G1T25S2	G2T15S1 and G2T25S2	G1T25S1 and G1T15S2	G2T25S1 and G2T15S2
V	890	803	7	0
P-value	$3.036*10^{-3}$	$6.391*10^{-4}$	$4.86*10^{-14}$	$3.679*10^{-14}$

Analyzing V values and p-values shown in Table 33, it is possible to conclude the following. All comparisons have p-values lower than 0.05, therefore, there is a median difference between every compared set of attached materials, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the attached materials was obtained when G2T25S1 and G2T15S2 were compared. This fact means, higher specific surface area and water absorption causes higher difference in attached materials, at least with the used samples and those experimental conditions. On the other hand, the lowest difference in the attached materials was obtained when G1T15S1 and G1T25S2 were compared. This fact means, lower specific surface area and water absorption causes lower difference in attached materials, at least with the used samples and those experimental conditions. In this group of comparisons, changing soil and temperature, it is interesting to notice, all comparisons have median difference, this fact prove that also temperature and soil have influence on attached materials.

Table 34 shows, the V values and p-values related with the comparison between sets of attached materials changing temperature and GUM, keeping constant the soil.

Table 34 Comparison between sets of attached materials (changing temperature and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T25S1	G1T25S1 and G2T15S1	G1T15S2 and G2T25S2	G1T25S2 and G2T15S2
V	1094	451	898	17
P-value	0.0564	$1.633*10^{-7}$	$3.471*10^{-3}$	$7.217*10^{-14}$

From the analysis of V values and p-values shown in Table 34, it is possible to conclude the following. When compare "G1T15S1 and G2T25S1" the p-value is higher than 0.05, then in this case, there is no median difference between those mentioned attached materials, it is possible assume that H_0 is true. On the other hand, in the case of the other three comparisons p-values are lower than 0.05, therefore, there is a median difference between every compared set of attached materials, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the attached materials was obtained when G1T25S2 and G2T15S2 were compared. This fact means, higher percentage of clay (S2) cause higher difference in attached materials, at least with the used samples and those experimental conditions. On the other hand, when compare G1T15S1 and G2T25S1 with lower percentage of clay (S1), there is no median difference between those mentioned attached materials, as mentioned before, therefore, in this case changing GUM and temperature does not has a great influence on attached materials. It is interesting to notice that, GUM-WS is the only change between the comparison with highest difference in attached materials and that one with not median difference in attached materials. As a conclusion, it is possible to state, changing GUM (difference specific surface area and water absorption) has a great influence on attached materials.

Table 35 shows, the V values and p-values related with the comparison between sets of attached materials changing soil and GUM, keeping constant the temperature.

Table 35 Comparison between sets of attached materials (changing soil and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T15S2	G1T25S1 and G2T25S2	G2T15S1 and G1T15S2	G2T25S1 and G1T25S2
V	0	588	1948	1042
P-value	$3.679*10^{-14}$	$5.966*10^{-6}$	0.0121	0.0295

After analyzing V values and p-values shown in Table 35, it is possible to conclude the following. All comparisons have p-values lower than 0.05, therefore, there is a median difference between every compared set of attached materials, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the attached materials was obtained when G1T15S1 and G2T15S2 were compared. This fact means, lower temperature (15°C) causes higher difference in attached materials, at least with the used samples and those experimental conditions. On the other hand, the lowest difference in the attached materials was obtained when G2T25S1 and G1T25S2 were compared. This fact means, higher temperature (25°C) causes lower difference in attached materials, at least with the used samples and those experimental conditions.

Table 36 shows, the V values and p-values related with the comparison between sets of attached materials changing soil, temperature and GUM at the same time.

Table 36 Comparison between sets of attached materials (changing soil, temperature and GUM)

Parameters	Comparison between sets of rate of suction			
	G1T15S1 and G2T25S2	G1T25S1 and G2T15S2	G2T25S1 and G1T15S2	G2T15S1 and G1T25S2
V	247	268	1510	1297
P-value	3.112×10^{-10}	6.236×10^{-10}	0.8098	0.3915

From the analysis of V values and p-values shown in Table 36, it is possible to conclude the following. When compare “G2T25S1 with G1T15S2” and “G2T15S1 with G1T25S2” the p-values are higher than 0.05, then in this case, there are no median difference between those mentioned attached materials, it is possible assume that H_0 is true. On the other hand, in the case of the other two comparisons, p-values are lower than 0.05, therefore, there are a median differences between every two compared sets of attached materials, then, H_0 is rejected. When p-value is lower than 0.05, it was explained what happen when this parameter is closer to alpha level or 0. Then, the highest difference in the attached materials was obtained when G1T15S1 and G2T25S2 were compared. Besides, when p-values are higher than 0.05, it was explained what happen when it is closer to 0.05 and when is farther from 0.05. Therefore, the most similar couple of data, changing soil, temperature and GUM is G2T25S1 and G1T15S2.

Table 37 shows, the V values and p-values related with the comparisons with highest difference in each set of conditions.

Table 37 Comparison with highest difference in each set of conditions

Parameters	Comparison with highest difference in each set of conditions						
	Changing soil (G2T15S1 and G2T15S2)	Changing temperature (G2T15S2 and G2T25S2)	changing GUM (G1T15S1 and G2T15S1)	changing soil and temperature (G2T25S1 and G2T15S2)	changing temperature and GUM (G1T25S2 and G2T15S2)	changing soil and GUM (G1T15S1 and G2T15S2)	changing soil, temperature and GUM G1T15S1 and G2T25S2
V	211	2926	516	0	17	0	247
P-value	9.205×10^{-11}	3.679×10^{-14}	9.566×10^{-7}	3.679×10^{-14}	7.217×10^{-14}	3.67×10^{-14}	3.112×10^{-10}

Analyzing the V values and p-values shown in Table 37, it is possible to conclude the following. The highest effect on attached materials, taking into consideration all kind of comparisons, was found when compare G1T15S1 with G2T15S2. This fact proves, it is not necessary change all factors to obtain a great difference of attached materials on the inner surface of the main pipe of the equipment, then, changing only the soil can has a great influence on the previous mentioned parameter. This fact prove the influence of soil on attached materials.

Table 38 shows, the V values and p-values related with the comparisons with lowest difference in each set of conditions or similar couple of data.

Table 38 Comparison with lowest difference in each set of condition or similar couple of data

Parameters	Comparison with lowest difference in each set of conditions						
	changing soil G1T15S1 and G1T15S2	changing temperature G1T15S2 and G1T25S2	changing GUM G1T25S1 and G2T25S1	changing soil and temperature G1T15S1 and G1T25S2	changing temperature and GUM G1T15S1 and G2T25S1	changing soil and GUM G2T25S1 and G1T25S2	changing soil, temperature and GUM G2T25S1 and G1T15S2
V	1336	1168	721	890	1094	1042	1510
P-value	0.5125	0.1273	$1.235*10^{-4}$	$3.036*10^{-3}$	0.0564	0.0295	0.8098

Analyzing the V values and p-values shown in Table 38, it is possible to conclude the following. The two most similar data, taking into consideration all kind of comparisons, were found when compare G2T25S1 with G1T15S2. It is very interesting to notice, in previous mentioned comparison, GUM, temperature and soil were changed, even though those changes, they did not affect the attached materials on the inner surface of the main pipe of the equipment.

Table 39 shows, the means of V values and means of p-values related with each type of comparisons.

Table 39 Means of Vvalues and p-values related with each type of comparison

Parameters	Comparison with lowest difference in each set of conditions						
	changing soil	changing temperature	changing GUM	changing soil and temperature	changing temperature and GUM	changing soil and GUM	changing soil, temperature and GUM
Mean (V)	704.5	2145	620.25	425	615	894.5	830.5
Mean (P-value)	0.1288	0.0332	$5.175*10^{-5}$	$9.188*10^{-4}$	0.0150	0.0104	0.3003

From the analysis of p-values shown in Table 39, it is possible to conclude that, changing only the GUM in the material to process was the variation, that most affect the attached materials on the inner surface of the main pipe of the equipment, at least with those experimental conditions and those used materials in the experiment. On the other hand, changing soil, temperature and GUM were the changes that less affect the attached materials on the inner surface of the main pipe of the equipment. At least, with those used materials and conditions in the experiments.

4.5 Summary of Chapter 4

It was proved through statistical analysis of the experimental results shown in section "**4.4 Results and discussion"** that considered factors (changing soil, temperature and GUM) can affect in several ways the controlled parameters (rate of suction, recovery and attached materials) in the apparatus, but in the case of recovery, while increasing the water content in the material to process there was no a defined tendency in the behaviour of this parameter. This fact, is because in "Chapter 3: Experimental Study on Soil Reduction Content in Grizzly under Materials", it was proved that recovery mainly depend on the frequency of vibration and pipe inclination angle, and those experimental factors were kept at a same value in this chapter .

Rate of suction of the equipment is the most important parameter to be checked, because it measures the capacity of the apparatus to reduce the initial soil content in the material to process as much as possible. From this fact, arise the necessity to find a numerical model in an attempt to predict the behaviour of rate of suction into consideration the specific conditions to process the contaminated GUM and its specifics characteristics.

Even those mentioned facts, the following partial conclusions can be drawn, taking into consideration the results, analysis, materials and experimental conditions described in this chapter:

- Temperature can has a double effect on equipment performance and the final result will depend on the characteristics of the materials to process.
- The equipment performance decreases while increasing the water content in the material to process.
- Changing all considered factors (changing soil, temperature and GUM) do not mean a bigger effect on rate of suction, recovery and attached materials.
- The highest effect on rate of suction, taking into consideration all kind of comparisons, was obtained when compare G1T15S1 with G1T15S2 and G1T25S2 with G2T15S2.
- The two most similar rate of suctions, taking into consideration all kind of comparisons, were found when compare G2T25S1 with G1T15S2.
- Changing only the soil or GUM and temperature at the same time, in the material to process were the variations, that most affect the rate of suction.
- The highest effect on recovery, taking into consideration all kind of comparisons, was obtained when compare G1T15S1 with G1T15S2.
- The two most similar recoveries, taking into consideration all kind of comparisons, were found when compare G1T15S2 with G2T25S2.
- Changing only the soil in the material to process was the variation, that most affect the recovery
- The highest effect on attached materials, taking into consideration all kind of comparisons, was obtained when compare G1T15S1 with G2T15S2.
- The two most similar attached materials, taking into consideration all kind of comparisons, were found when compare G2T25S1 with G1T15S2.
- Changing the GUM and soil at the same time, in the material to process were the variations, that most affect the attached materials on the inner surface of the main pipe of the equipment.

CHAPTER 5 SIMULATION ON REDUCTION OF SOIL CONTENT IN GUM.

CHAPTER 5 SIMULATION ON REDUCTION OF SOIL CONTENT IN GUM.

5.1 Data analysis. Determination of numerical model. Rate of suction.

As mentioned in the section "**4.5 Summary of Chapter 4**", it is necessary to find a numerical or mathematical model in an attempt to predict the behaviour of rate of suction, taking into consideration the specific conditions to process the contaminated GUM and its specifics characteristics.

In Chapter 4, it was used a simple polynomial regression (a case of simple linear regression), because in that case there was one dependent variable (rate of suction, recovery or attached materials) and one independent variable (water content in the material to process). But, this time, analyzing the data to be used in the process to determine the numerical model, it is still one dependent variable but there are several independent variables.

The independent variables will be the specific characteristics of GUM and soil, besides the experimental conditions to be used for carrying out the experiments. Therefore the independent variable are: water content in the material to process [wc], water absorption of GUM [g.a], specific surface area of GUM [g.sa], clay percent of soil [s.c], silt percent of soil [s.s], sand percent of soil [s.sa], liquid limit of soil [s.LL], shrinkage limit of soil [s.SL], temperature in the laboratory [t]. Then, in this case it is not possible to use the simple polynomial regression to obtain a numerical model to predict the behaviour of the mentioned parameter. Then, it was proposed to use multiple linear regression.

Multiple linear regression refers to regression applications in which there are more than one independent variables. Multiple regression includes a technique called polynomial regression, as mentioned before. In polynomial regression it is possible regress a dependent variable on powers of the independent variables [51]. Polynomial regression is a case of linear regression, therefore this procedure can be used with one or several independent variables.

The basic multiple regression model of a dependent (response) variable Y on a set of k independent (predictor) variables $X_1, X_2, \ldots, X_k$ can be expressed as [51]:

$Y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_k x_{ik} + e_i$ for i = 1, 2, …, n (10)

where Y_i is the value of the dependent variable Y for the ith case, x_{ij} is the value of the jth independent variable X_j for the ith case, β_0 is the Y-intercept of the regression surface (think multidimensionality), each β_j, j = 1, 2,…, k , is the slope of the regression surface with respect to variable X_j and e_i is the random error component for the ith case. In previous mentioned basic equations, there is n observations and k predictors ($n > k + 1$) [51].

The assumptions of the multiple regression model are similar to those for the simple linear regression model. Model assumptions [51]:

- For each observation the errors e_i are normally distributed with mean zero and standard deviation σ and are independent of the error terms associated with all other observations. The errors are uncorrelated with each other. That is $e_i \sim N(0,\sigma 2)$ for all i = 1,2,…,n , independent of other errors [51].
- In the context of regression analysis, the variables X_j are considered fixed quantities, although in the context of correlation analysis, they are random variables. In any case, X_j are independent of the error term. When it is assumed that X_j are fixed quantities, it is also assumed the realizations of k variables X_j and the only randomness in Y comes from the error term [51].

It will be used RStudio version 0.99.887 to obtain the numerical model to predict the rate of suction (RS) of the equipment, taking into consideration the defined independent variables. Table 40 shows an example how the data were organized to be processed by the software, second and third row of the table show the data related with GUM-WS1 and Soil 1 when set 15°C in the laboratory. Fourth and fifth row of the table show the data related with GUM-WS2 and Soil 2 when set 25°C in the laboratory. All data were combined to obtain a matrix with 104 rows and 10 columns.

Table 40 Organization of data to be used processed by software

wc (%)	g.a (%)	g.sa (m^2/kg)	s.c (%)	s.s (%)	s.sa (%)	s.LL (%)	s.SL (%)	Temp (°C)	RS (%)
0.325	1.714	1.66	1.2	93.6	5.2	37.0	26.66	15.0	5.20
0.650	1.714	1.66	1.2	93.6	5.2	37.0	26.66	15.0	5.24
0.325	1.821	2.08	11.1	67.1	21.8	48.1	22.13	25.0	4.47
0.650	1.821	2.08	11.1	67.1	21.8	48.1	22.13	25.0	4.45

After trying to find the mentioned numerical model using the multiple linear regression procedure, explained before, it was impossible to obtain the parameters β_j, then it is not possible to find a numerical model to predict the equipment performance, at least with the mentioned procedure. It means that the relationship between β_j and x_{ij} is not linear. Therefore, it is necessary to use another tool to find the numerical model.

Nonlinear least squares regression extends linear least squares regression for use with a much larger and more general class of functions. Almost any function that can be written in closed form can be incorporated in a nonlinear regression model. Unlike linear regression, there are very few limitations on the way parameters can be used in the functional part of a nonlinear regression model. The way in which the unknown parameters in the function are estimated, it is conceptually the same as it is in linear least squares regression [45].

Nonlinear regression models are those that are not linear in the parameters [52] or a model in which at least one of the parameters appears nonlinearly. More formally, in a nonlinear model, at least, one derivative with respect to a parameter should involve that parameter [53].

As the name suggests, a nonlinear model is any model of the basic form [45],

$$y = f(\vec{x}, \vec{\beta}) + \varepsilon \quad (11)$$

in which, the functional part of the model is not linear with respect to the unknown parameters, β_0, β_1, etc and the method of least square is used to estimate the values of the unknown parameters [45].

Due to the way in which the unknown parameters of the function are usually estimated, however, it is often much easier to work with models that meet two additional criteria [45]:

1. The function is smooth with respect to the unknown parameters.
2. The least square criterion that is used to obtain the parameter estimates has a unique solution.

These last two criteria are not essential parts of the definition of a nonlinear least squares model, but they have a practical importance [45].

How do you choose the right model to fit data? In some applications of non-linear regression, you already know the model you want to fit, as it arises from theory. For example: the Michaelis-Menten model, very commonly applied in enzyme kinetics [54].

There are many other processes that are inherently nonlinear. For example, the strengthening of concrete as it cures is a nonlinear process. Research on concrete strength shows that the strength increases quickly at first and then levels off, or approaches an asymptote in mathematical terms, over time [45]. Besides, in agriculture there is a reference table as a guide line to understand the family of function with application in this field, for instance:

Exponential function, Sigmoid functions, Photosynthesis function and Temperature dependencies function [55].

In other cases you have to choose a model from various options, and select the best fitting one, or the one that has certain properties. One reason to apply non-linear regression is that the model can be expected to behave well outside the range of the data used for fitting. Models with an asymptote are a good example [54].

It was tried to find a previous nonlinear numerical model related with the soil reduction content activity in recycled asphalt aggregate, but it was impossible. Then, it was necessary to find models in other fields and after, trying to adapt it to the collected data in this research. Afterward analyze many kind of models to be used as a base to obtain a numerical model to predict the equipment performance it were selected two functions for trying to adapt them to the results in this research. The selection was carried out, taking into consideration that, the function graph should decrease while increasing the value in horizontal axis, because that is the behaviour of rate of suction when increases the water content in the sample to process.

As a first candidate model to be considered to adapt it to the collected data in this research, it was proposed exponential decay. This model is a specific case of exponential function that is used in agriculture. The exponential decay is applied in a wide spectrum of soil and plant sciences, besides it is commonly used to describe light and N vertical distributions within plant canopies [55]. A general exponential decay is defined as:

$Y(t) = Y_0 * e^{(-kt)}$ (12)

where Y is the response variable (e.g, soil organic matter), t is the explanatory variable (e.g, time), Y_0 is the initial or the maximum Y value, k is a rate constant that determines the steepness of the curve [55].

As a second candidate model to be considered to adapt it to the collected data in this research, it was proposed one case of Hill functions. These functions were introduced by A. V. Hill in 1910 to describe the binding of oxygen to hemoglobin. Subsequently, they have been widely used in biochemistry, physiology, and pharmacology to analyze the binding equilibria in ligand-receptor interactions. The selected function was a monotonic decreasing function of ligand molecules B, defined as:

$h(x) = \frac{1}{1+x^n}$ (13)

by defining $x = ([B])/K$, where n is the number of ligand molecules B and K is the reaction dissociation constant [56].

Then, it is necessary to adapt those previous mentioned model to soil reduction content activity in GUM taking into consideration the defined independent variable in this chapter. Besides, it is necessary to find the optimum parameters for those independent variables, in an attempt to find an optimum numerical model.

One way to determine the unknown parameters can be by using the Gauss-Newton method, where the value of sum squares of error is minimized. The efficiency of the Gauss-Newton algorithm has been proven [57]. Therefore, it was decided to use the Gauss-Newton method to determine the unknown parameter in this research.

Gauss-Newton Method state that, an optimization problem occurs when an objective function (mentioned model) is, either minimized or maximized, over a set of constraints. When, the nonlinear least squares problem is formulated as an optimization problem, where the sum squares of error (SSE) is defined as an objective function. During the computation procedure, the SSE is minimized, whereas the unknown parameters in the proposed model are determined in the optimal sense. In case of nonlinear least squares problem, which is an unconstraint optimization problem, is defined by [57].

$$\min_{x \epsilon R^n} f(x) = \frac{1}{2} r(x)^T r(x) = \frac{1}{2} \sum_{i=1}^{m} \left(r_i(x)\right)^2 \quad (14)$$

where $f(x): R^n \rightarrow R$ is the objective function, and $r_i(x)$ is the residual function, which is defined by [57]

$$r_i(x) = \phi(t_i, x) - y_i, i = 1,2, \dots, m, \quad (15)$$

where $\phi(t_i, x)$ is the proposed function and y_i is the observation data. The gradient of $f(x)$ is given by [57]

$$g(x) = J(x)^T r(x) \quad (16)$$

where $J(x)$ is the Jacobian matrix of the residual function $r(x)$. The Hessian matrix is give by [57]

$$G(x) = \sum_{i=1}^{m} \left(S_i(x) + \nabla r_i(x)^T \nabla r_i(x)\right) \quad (17)$$

where $S(x) = \nabla^2 r(x) r(x)$ (18)

The "T" in the terms $J(x)^T$ and $\nabla r_i(x)^T$, represent the transpose of the corresponding matrix, it means a new matrix whose rows are the columns of the original one.

In the case of the symbol "∇" represent the gradient of the corresponding matrix. In an attempt to explain the meaning of gradient, let consider X as a "n x n" matrix with elements x_{ij}. Let consider $f(X)$ as a scalar, real-valued function of the x_{ij} [58]:

$f(X) = f(x_{11}, \dots, x_{1n}, x_{21}, \dots, x_{2n}, \dots)$ (19)

it is possible the partial derivatives,

$\frac{\partial f(X)}{\partial x_{ij}}$ $; i, j = 1, 2, \dots, n$ (20)

It is possible to define an "n x n" matrix $\frac{\partial f(X)}{\partial X}$, called the gradient matrix of $f(X)$ with respect to X, as the matrix whose ij-th elements is given by $\frac{\partial f(X)}{\partial x_{ij}}$ [58].

In the case of constrained optimization is a set of procedure (for this research Gauss-Newton Method) for the solution of the general nonlinear programming problem "$\min f(x)$" [59]. Then, it is possible define:

linear constrains: $Ax = B\ ,\ Cx \geq D$

nonlinear constrain: $G(x) = 0\ ,\ H(x) \geq 0$

and bounds: $x_l \leq x \leq x_u$

where $G(x)$ and $H(x)$ are functions provided by the researcher and must be differentiable at least once with respect to x [59].

Therefore, in the specific case of this research is possible to obtain:

$\min_{x \epsilon R^n} f(wc, g.a, g.sa, s.c, s.s, s.sa, s.LL, s.SL, t) = \frac{1}{2}\sum_{i=1}^{m}\left(r_i(wc, g.a, g.sa, s.c, s.s, s.sa, s.LL, s.SL, t)\right)^2$ (21)

and the proposed functions are:

$Y(wc, g.a, g.sa, s.c, s.s, s.sa, s.LL, s.SL, t) = Y_0 * e^{(-(a*wc+b*g.a+c*g.sa+d*s.c+e*s.s+f*s.sa+g*s.LL+h*s.SL+i*t))}$ (22)

$h(wc, g.a, g.sa, s.c, s.s, s.sa, s.LL, s.SL, t) = \frac{a*\left(\frac{g.a}{g.sa}\right)+b*\left(\frac{s.sa}{s.s}\right)+c*\left(\frac{s.LL}{s.SL}\right)}{d*t+e*s.c+wc^8}$ (23)

and the restrictions are:

$wc > 0, g.a > 0, g.sa > 0, s.c > 0, s.s > 0, s.sa > 0$

Perhaps the biggest nuisance with the algorithm (Gauss-Newton Method) used in this research is the need to supply bounds and starting values (for parameters) . The convergence of the algorithm depends heavily upon supplying appropriate starting values. One accepted method for obtaining a good set of starting values is to estimate them from the data [52]. It can be analytically or graphically.

After many times trying to adjust the formula 22 to the data in this research and obtain the values of unknown parameters, it was impossible, because at the beginning of iteration it was obtained all the time, a singular gradient matrix. Singular gradient matrix is returned by the RStudio, when the problem matrix is nearly singular (or non-invertible) [60] [61]. This error message is a side effect of the underlying nonlinear least-squares algorithm, and is usually dependent on your chosen starting values [60] [62].

Singular gradient matrix means that the Jacobian matrix J(x) of r(x) is nearly rank deficient [60] and it refers to the derivative of the vector of predicted values with respect to the vector of parameters at the current parameter estimates [62]. Therefore, from this fact, it is not possible to determine the values of unknown parameters.

All procedures for nonlinear parameter estimation require initial values. The choice of values will influence the convergence of the estimation algorithm, in the worst case yielding no convergence and in the best case convergence in a few iterations, however there is no standard procedure for getting initial estimates. One practical method is the usage of graphical exploration [55]. Therefore, in an attempt to explain why it was impossible to find values for unknown parameters in formula 22, it will be used a graph, with specific characteristics. In Figure 71 blue line "Real RS" represents the rate of suction of the equipment when processing the GUM-WS1 with temperature 15°C and soil 1, besides, red line "Estimated RS" represents the estimated rate of suction of the equipment when processing the GUM-WS1 with temperature 15°C and soil 1, considering the following parameter values in formula 22: $a = 0.5$, $b = 0.02$, $c = 0.01$, $d = 0.01$, $e = 0.008$, $f = 0.01$, $g = 0.003$, $h = 0.002$, $i = 0.1$ and $Y_0 = 90$.

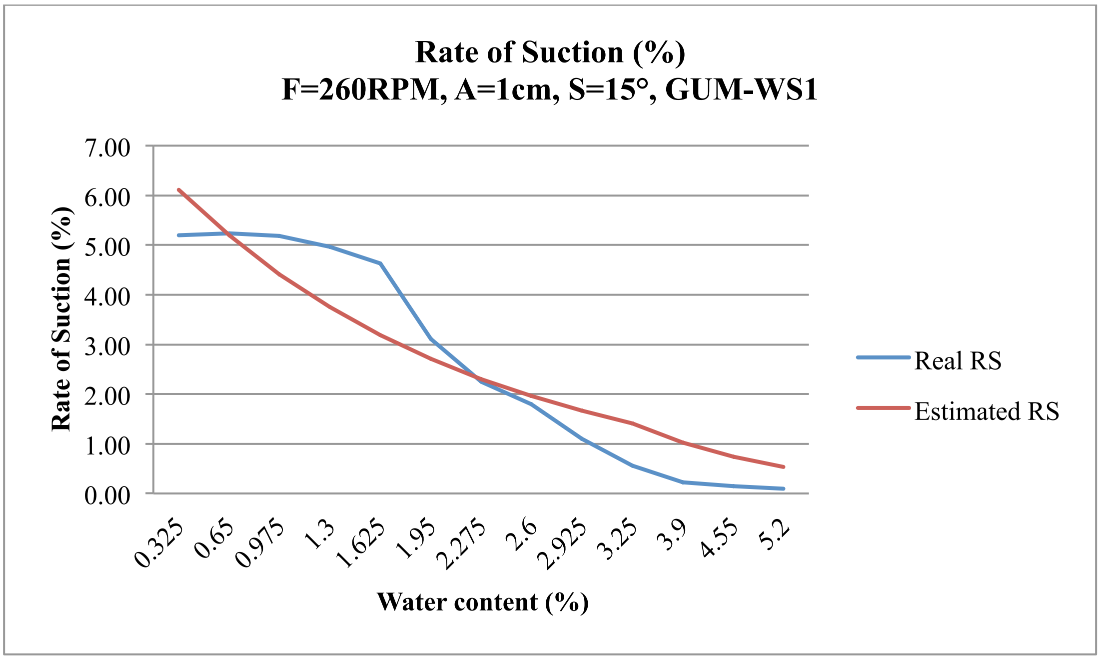

Fig. 71 Relationship between Rate of Suction and Water Content (F=260RPM, A=1cm, S=15 and GUM-WS1)

After analyzing the Figure 71, it is possible to notice that, both graph (blue and red line) decreases when increasing the water content in the material to process. But, blue line (Real RS), starts with decreasing concave shape and then become decreasing convex shape, while increasing the water content in the material to process, besides, red line (Estimated RS), keep constant a decreasing convex shape while increasing the water content in the material to process. Even, it was changed the parameter values, the red line (Estimated RS) never started with decreasing concave shape and then became decreasing convex shape, while increasing the water content in the material to process. That is the necessary shape for red line, to simulate better the rate of suction of the equipment. Therefore, formula 22 it is not convenient to simulate the equipment performance.

In the case of formula 23, it was used the graphical exploration to obtain the initial values for parameters. Then, it was used Gauss-Newton Optimization Method to obtain optimum value for each parameter in formula 23. Afterwards, the results are shown in Table 41.

Table 41 Results from Gauss-Newton optimization method

	a	b	c	d	e
Values	1191.57	25041.09	-349.79	11.62	164.85

Therefore, taking into consideration each parameter value the formula 23 will be as follow:

$$h(wc, g.a, g.sa, s.c, s.s, s.sa, s.LL, s.SL, t) = \frac{1191.57*\left(\frac{g.a}{g.sa}\right)+25041.09*\left(\frac{s.sa}{s.s}\right)-349.79*\left(\frac{s.LL}{s.SL}\right)}{11.62*t+164.85*s.c+wc^{8}} \quad (24)$$

Now, it is necessary to verify the goodness of the model. There is no single method or index to best assess the goodness of fit, but there are many different methods (graphical and numerical) that highlight different features of the data and the model. Graphical comparison provides a quick visual assessment of the goodness of fit. Numerical statistical indices provide the additional detail needed to assess the goodness of fit [55].

One way to assess the strength of fit is to consider how far off the model is for a typical case. That is, for some observations, the fitted value will be very close to the actual value, while for others it will not. The magnitude of a typical residual can give us a sense of generally how close our estimates are [63].

However, recall that some of the residuals are positive, while others are negative. In fact, it is guaranteed by the least squares fitting procedure that the mean of the residuals is zero. Thus, it makes more sense to compute the square root of the mean squared residual, *or* root mean squared error *(RMSE). RStudio (software) calls this quantity the* residual standard error (RSE) and it is shown in the following formula [63].

$$RMSE = RSE = \sqrt{\frac{\sum_{i=1}^{n} {e_i}^2}{d.f.}} = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{n - n.par}} \quad (25)$$

where e_i are the residuals (errors), $d.f.$ is the degree of freedom, n is the number of data points, Y_i and $\hat{Y}_i$ are the observed and predicted values, respectively and $n.par$ is the number of parameters in the model [54]. It is easy to realize that, the lower is the value of RMSE (or RSE) the better goodness of the model.

Another way to assess the goodness of fit is the coefficient of efficiency E. This coefficient has been widely used to evaluate the performance of models. Nash and Sutcliffe in 1970 defined the coefficient of efficiency which ranges from minus infinity to 1.0, with higher values indicating better agreement [64]. The formula is as follow:

$$E = 1.0 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2} \quad (26)$$

where O_i, P_i, $\bar{O}_i$ and $N$are the observed values, predicted values, observed mean and the number of observation respectively.

Physically, E is the ratio of the mean square error to the variance in the observed data, subtracted from unity. For example, if the square of the differences between the model simulations and the observations is a large as the variability in the observed data, then $E = 0.0$, and if it exceeds it, then $E < 0.0$ (i.e., the observed mean is a better predictor than

P_i). Thus a value of zero for the coefficient of efficiency indicates that the observed mean $\bar{O}$ is a good predictor as a model, while negative values indicate that the observed mean is a better predictor than the model [64].

Willmott in 1981 proposed the index of agreement d, given by [64]:

$$d = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} = 1.0 - N\frac{MSE}{PE} \quad (27)$$

where O_i, P_i, $\bar{O}_i$, N are the observed values, predicted values, observed mean and the number of observation respectively. Besides, MSE and PE are the mean square error and potential error respectively.

The index of agreement varies from 0.0 to 1.0, with higher values indicating better agreement between the model and observations. Willmott in 1984, argued that the index of agreement represented the ratio between the mean square error and the potential error (PE), multiplied by N and then subtracted from the unit. Potential error was defined as [64]:

$$PE = \sum_{i=1}^{N}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2 \quad (28)$$

Table 42, shows the number of observations and parameters, RMSE (or RSE), E and d related with the formula 24.

Table 42 Characteristics related with formula 24

	Number of observations	Number of parameters	RMSE (or RSE)	E	d
Values	104	5	0.509	0.930	0.983

After analyzing the results from Table 42, it is possible to realize that, RMSE has a low value, as mentioned before, the lower is the value of RMSE (or RSE) the better goodness of the model. Besides, in the case of E and d, as mentioned before, higher values indicate better agreement between model and observations, then those values are close to 1, that is the value that indicate the perfect agreement between the model and the observations. It is possible to conclude that, there is a good agreement between the formula 24 and observations.

Previous parameters (RMSE, E and d) are examples of numerical methods to assess the goodness of fit, but as mentioned before there are also graphical methods that highlight different features of the data and the model.

The plot of raw residuals against fitted values (predicted values using the model) is useful for assessing whether or not the chosen model equation is appropriate. (the scatter is similar above and below the horizontal axis along the range of fitted values in case of an appropriate model equation) [65]. Figure 72 shows the residuals vs fitted values related with formula 24.

$$res_i = Y_i - \hat{Y}_i \quad (29)$$

$$\hat{Y}_i = h_i(wc_i, g.a_i, g.sa_i, s.c_i, s.s_i, s.sa_i, s.LL_i, s.SL_i, t_i) = \frac{1191.57*\left(\frac{g.a_i}{g.sa_i}\right)+25041.09*\left(\frac{s.sa_i}{s.s_i}\right)-349.79*\left(\frac{s.LL_i}{s.SL_i}\right)}{11.62*t_i+164.85*s.c_i+wc_i^{8}} \quad (30)$$

where res_i represents the residuals values, Y_i and $\hat{Y}_i$ are the observed and fitted values.

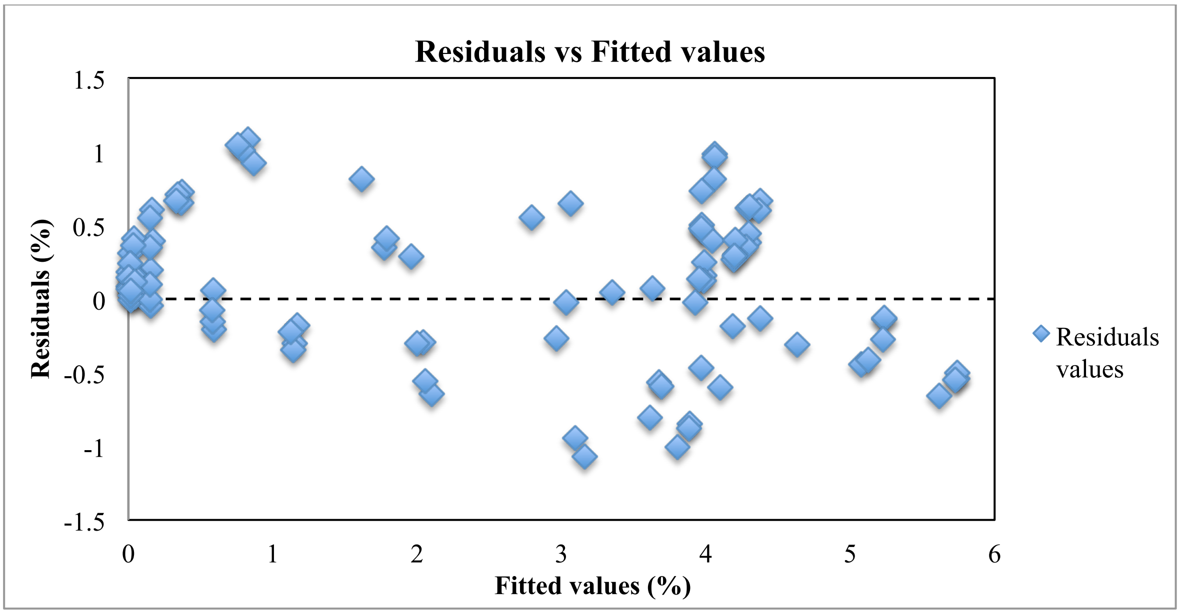

Fig. 72 Graph of residuals vs fitted values related with formula 24

It is possible to notice from Figure 72 that, the scatter of dots is not similar above and below the horizontal axis along the range of fitted values. Then taking into consideration this fact it is possible to conclude the following, the analysis of Figure 72 gives the idea that formula 24 is not very suitable to simulate the rate of suction of the equipment.

Another graphical method that is possible to use is the plot of the standardized residuals vs. the fitted values, because it is useful for evaluation if there is any indication of variance inhomogeneity, which would show up as an uneven spread across the range of the fitted values [65]. Standardized residuals are obtained by dividing the residuals by the residual standard error [65].

$$std.res_i = \frac{res_i}{SEM} \quad (31)$$

$$SEM = \frac{S}{\sqrt{n}} \quad (32)$$

$$S^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \quad (33)$$

where x_i, $\bar{x}$ and n are the observed values, the mean of observed values and number of observation. In the case of $std.res_i$, SEM and S^2 are the standardized residuals, standard error of the mean and variance respectively [66]. Figure 73 shows the standardized residuals vs fitted values related with formula 24.

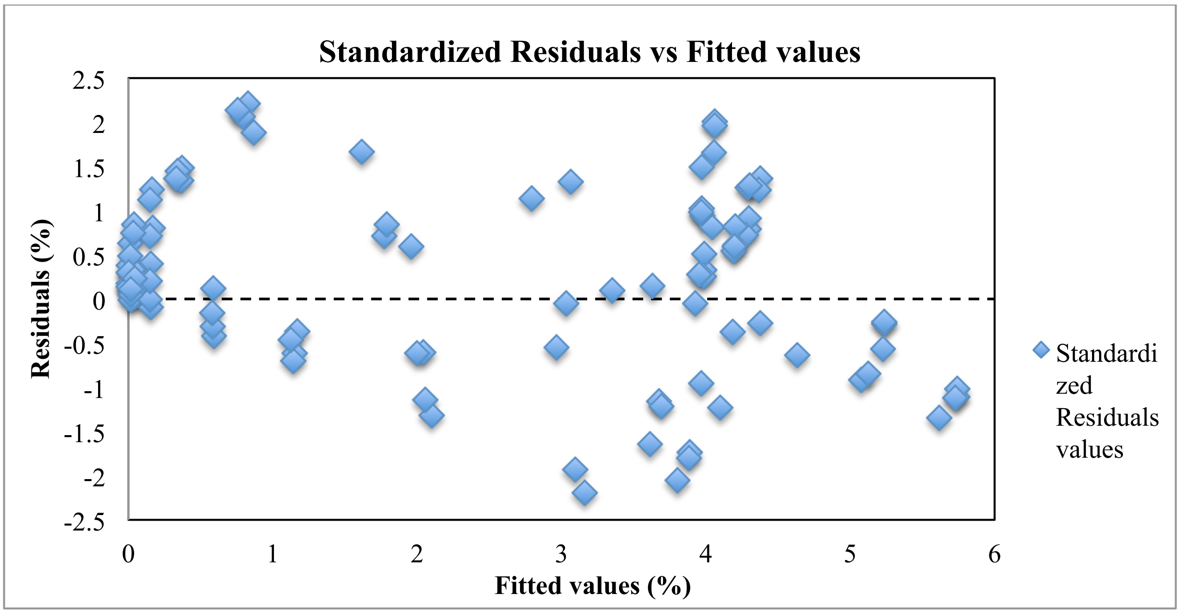

Fig. 73 Graph of Standardized residuals vs fitted values related with formula 24.

After analyzing the Figure 73, it is possible to conclude that, the scatter of dots is not homogeneous, therefore there is an uneven spread of across the range of the fitted values. Then there is an indication of variance inhomogeneity.

In addition to the visual assessment of the model assumptions, the normality of residuals may be evaluated using the Shapiro-Wilk test. This test is one of the most powerful tests of normality [65], as mentioned before. Then, it will be used the formula number 7 to calculate the statistics of Shapiro-Wilk test. Besides, the alpha level (α) will be set at 0.05, it means that confidence level will be set at 95%.

- Null hypothesis (H_0) : the sample data are not significantly different from a normal distribution.
- Alternative hypothesis (H_a): the sample data are significantly different from a normal distribution.

If p-value is more than alpha level (0.05), it is possible to be 95% certain that the data are normally distributed, in other words, it is possible assume that H_0 is true. If p-value is less than or equal to alpha level (0.05), it is possible to be 95% certain that the data are not normally distributed, in other words, it is possible assume that H_0 is false. Table 43 shows the results obtained from Shapiro-Wilk test, related with the normality evaluation of residuals.

Table 43 Shapiro-Wilk test results (residuals)

	Alpha level	Confidence level	Statistic (W)	P-value
Values	0.05	95%	0.9866	0.3815

Analyzing the data from Table 43, it is possible to realize that p-value is higher than 0.05, then it is possible to be 95% certain that the residuals related with the formula 24 are normally distributed, so H_0 is true.

After considering all results, from graphical and numerical method to verify the goodness of fit, related with formula 24, it was concluded that it is necessary to improve a little bit the goodness of formula 24, in an attempt to simulate better the rate of suction of the equipment. Analyzing the structure of the formula 24, it was noticed that changing the exponent of water content can help the predicted values be closer to observation (real rate of suction). Then the new model proposition be will as follow:

$$h(wc, g.a, g.sa, s.c, s.s, s.sa, s.LL, s.SL, t) = \frac{a*\left(\frac{g.a}{g.sa}\right)+b*\left(\frac{s.sa}{s.s}\right)+c*\left(\frac{s.LL}{s.SL}\right)}{d*t+e*s.c+wc^{4+f*s.c}} \quad (34)$$

In the case of formula 34, it was used the graphical exploration to obtain the initial values for parameters. Then, it was used Gauss-Newton Optimization Method to obtain optimum value for each parameter in the mentioned formula. Afterwards, the results are shown in Table 44.

Table 44 Results from Gauss-Newton optimization method

	a	b	c	d	e	f
Values	84.58	3267.62	-80.4	0.395	18.73	0.216

Therefore, taking into consideration each parameter value from Table 44, the formula 34 will be as follow:

$$h(wc, g.a, g.sa, s.c, s.s, s.sa, s.LL, s.SL, t) = \frac{84.58*\left(\frac{g.a}{g.sa}\right)+3267.62*\left(\frac{s.sa}{s.s}\right)-80.4*\left(\frac{s.LL}{s.SL}\right)}{0.395*t+18.73*s.c+wc^{4+0.216*s.c}} \quad (35)$$

Then, to evaluate the goodness of fit, it will be used the formula 25, 26 and 27 to determine RMSE, E and d respectively. Table 45, shows the number of observations and parameters, RMSE (or RSE), E and d related with the formula 32 and 24, with the goal to compare them each other.

Table 45 Characteristics related with formula 32

	Number of observations	Number of parameters	RMSE (or RSE)	E	d
Values (Formula 32)	104	6	0.285	0.978	0.994
Values (Formula 24)	104	5	0.509	0.930	0.983

After analyzing the results from Table 45, it is possible to realize that, RMSE related with formula 32 is lower than this value related with formula 24, as mentioned before, the lower is the value of RMSE (or RSE) the better goodness of the model, therefore taking into consideration the information from this parameter, formula 32 has better performance to simulate the rate of suction of the equipment. Besides, in the case of E and d related with formula 32 are higher than those values related with formula 24, as mentioned before, higher values of E and d indicate better agreement between model and observations, hence it is possible to conclude that, performance of formula 32 is higher than the performance of formula 24.

In an attempt to verify graphically the goodness of fit, related with formula 32, it will be plotted the raw residuals against fitted values, with the goal to evaluate is the mentioned formula is suitable or not to simulate the equipment performance. Figure 74 shows the residuals vs fitted values related with formula 32.

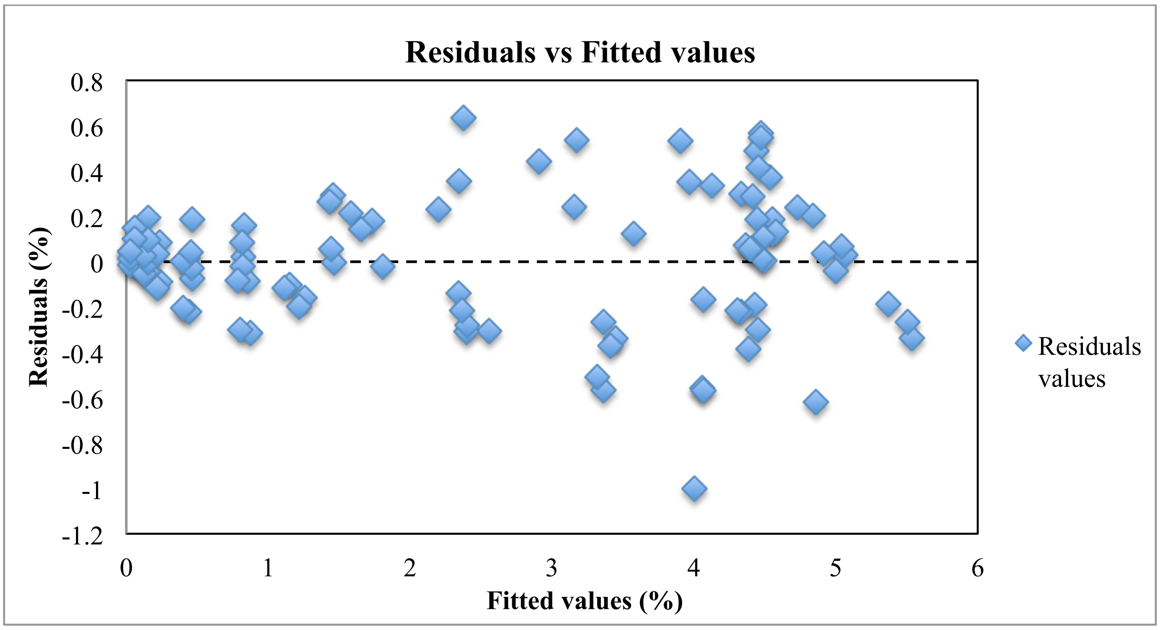

Fig. 74 Graph of residuals vs fitted values related with formula 32

It is possible to notice from Figure 74 that, this time the scatter of dots look pretty similar above and below the horizontal axis along the range of fitted values. Then taking into consideration this fact it is possible to conclude the following, the analysis of Figure 74 gives the idea that formula 32 is suitable to simulate the rate of suction of the equipment.

Another graphical method to be considered is the plot of the standardized residuals vs. the fitted values, as mentioned before, because it is useful for evaluation if there is any indication of variance inhomogeneity. Figure 75 shows the standardized residuals vs fitted values related with formula 32.

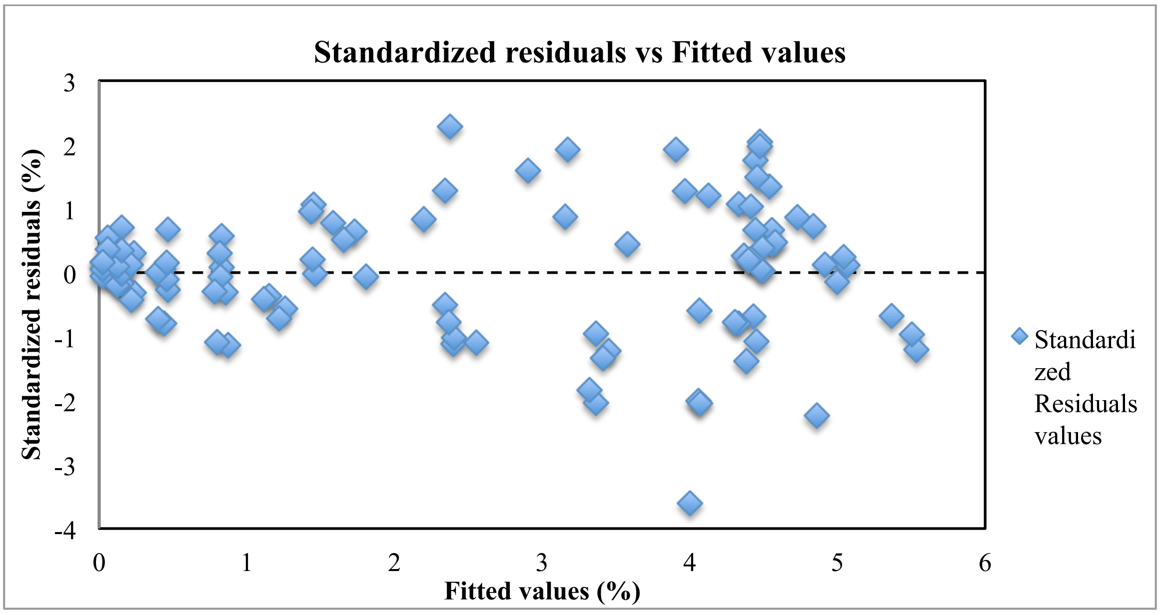

Fig. 75 Graph of standardized residuals vs fitted values related with formula 24)

After analyzing the Figure 75, it is possible to conclude that, the scatter of dots look pretty homogeneous, therefore there is an balanced distribution across the range of the fitted values. Then there is an indication of variance homogeneity.

In addition to the visual assessment of the model assumptions, the normality of residuals may be evaluated using the Shapiro-Wilk test, as mentioned before. Then, it will be used the formula number 7 to calculate the statistics of Shapiro-Wilk test. Besides, the alpha level (α) will be set at 0.05, it means that confidence level will be set at 95%.

- Null hypothesis (H_0) : the sample data are not significantly different from a normal distribution.
- Alternative hypothesis (H_a): the sample data are significantly different from a normal distribution.

If p-value is more than alpha level (0.05), it is possible to be 95% certain that the data are normally distributed, in other words, it is possible assume that H_0 is true. If p-value is less than or equal to alpha level (0.05), it is possible to be 95% certain that the data are not normally distributed, in other words, it is possible assume that H_0 is false. Table 46 shows the results obtained from Shapiro-Wilk test, related with the normality evaluation of residuals.

Table 46 Shapiro-Wilk test results (residuals)

	Alpha level	Confidence level	Statistic (W)	P-value
Values	0.05	95%	0.9788	0.0935

Analyzing the data from Table 46, it is possible to realize that p-value is higher than 0.05, then it is possible to be 95% certain that the residuals related with the formula 32 are normally distributed, so H_0 is true.

After considering all results, from graphical and numerical method to verify the goodness of fit, related with formula 32, it was concluded that the mentioned formula is suitable for simulating the equipment performance, taking into consideration the previous analysis. Therefore, formula 32 is better than formula 24. Besides, carry out the last assessment of formula 32 and 24, Figure 76, 77, 78, 79, 80, 81, 82 and 83 show the observed and simulated rate of suction of the equipment, obtained from formula 24 (left side) and formula 32 (right side) while process G1T15S1, G1T15S2, G1T25S1, G1T25S2, G2T15S1, G2T15S2, G2T25S1, G2T25S2 respectively.

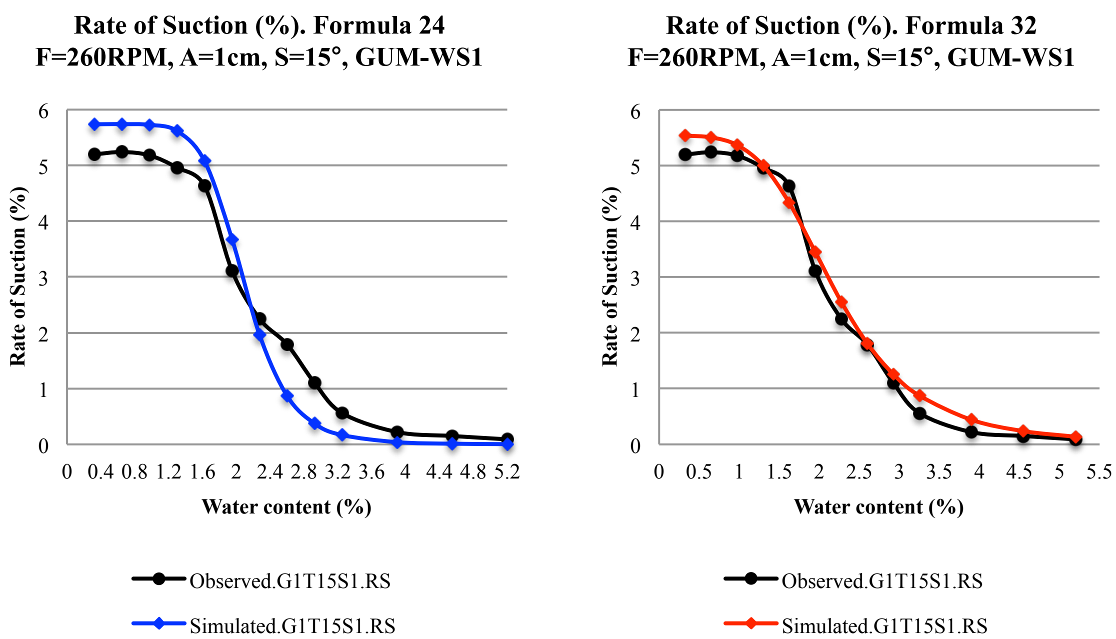

Fig. 76 Observed (G1T15S1) and simulated rate of suction (formula 24 left side and 32 right side)

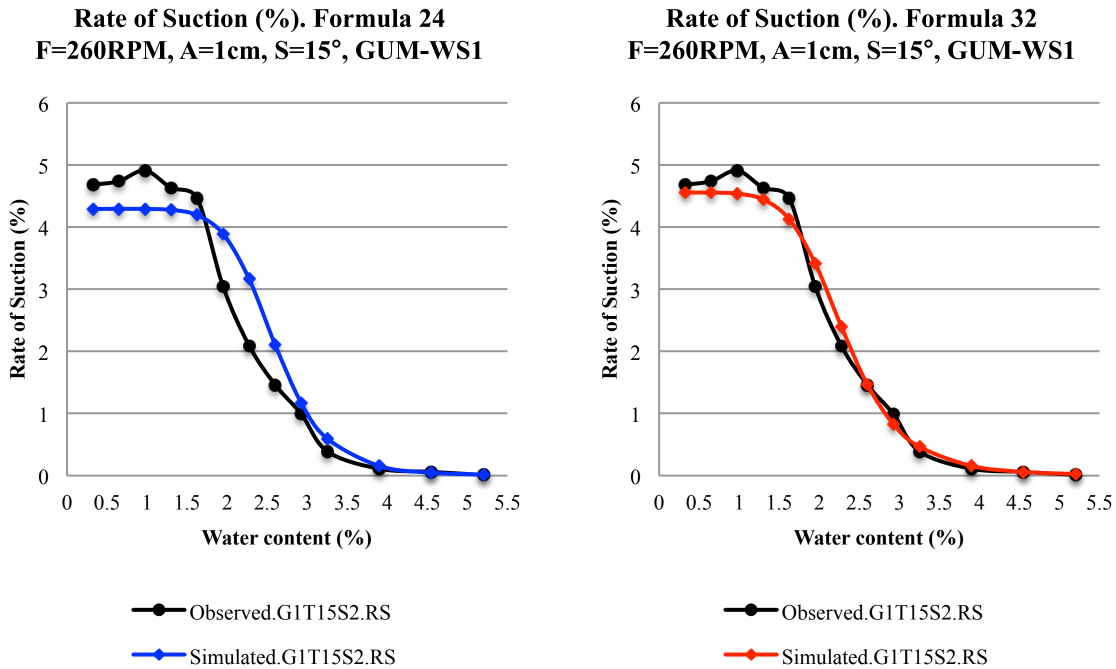

Fig. 77 Observed (G1T15S2) and simulated rate of suction (Formula 24 left side and 32 right side)

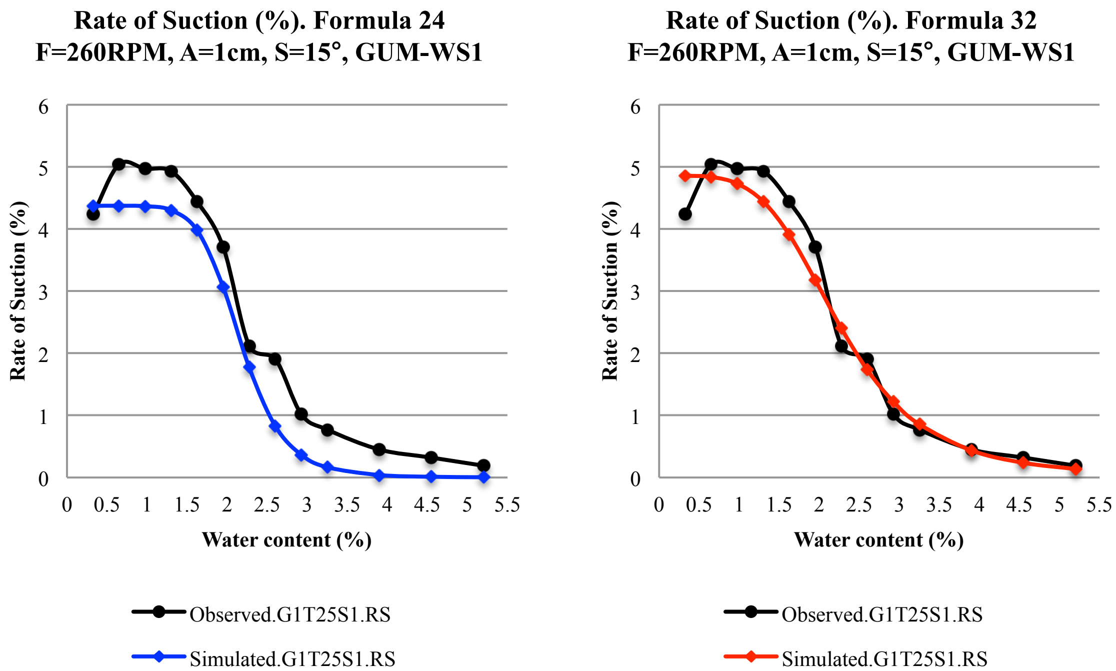

Fig. 78 Observed (G1T25S1) and simulated rate of suction (formula 24 left side and 32 right side)

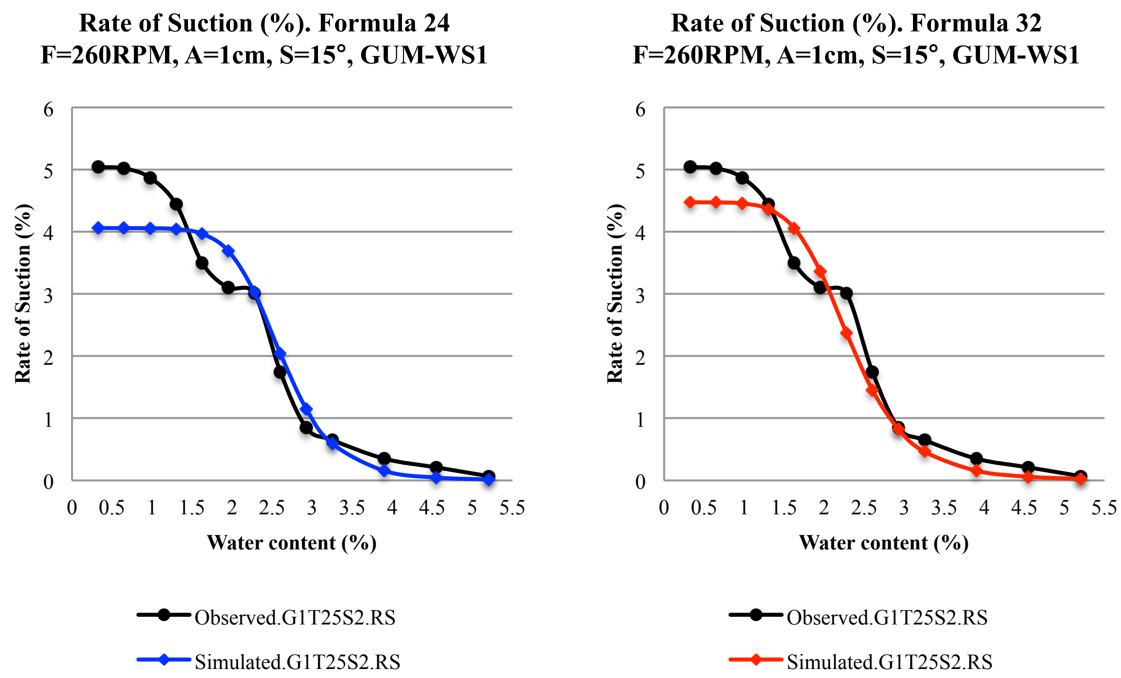

Fig. 79 Observed (G1T25S2) and simulated rate of suction (formula 24 left side and 32 right side)

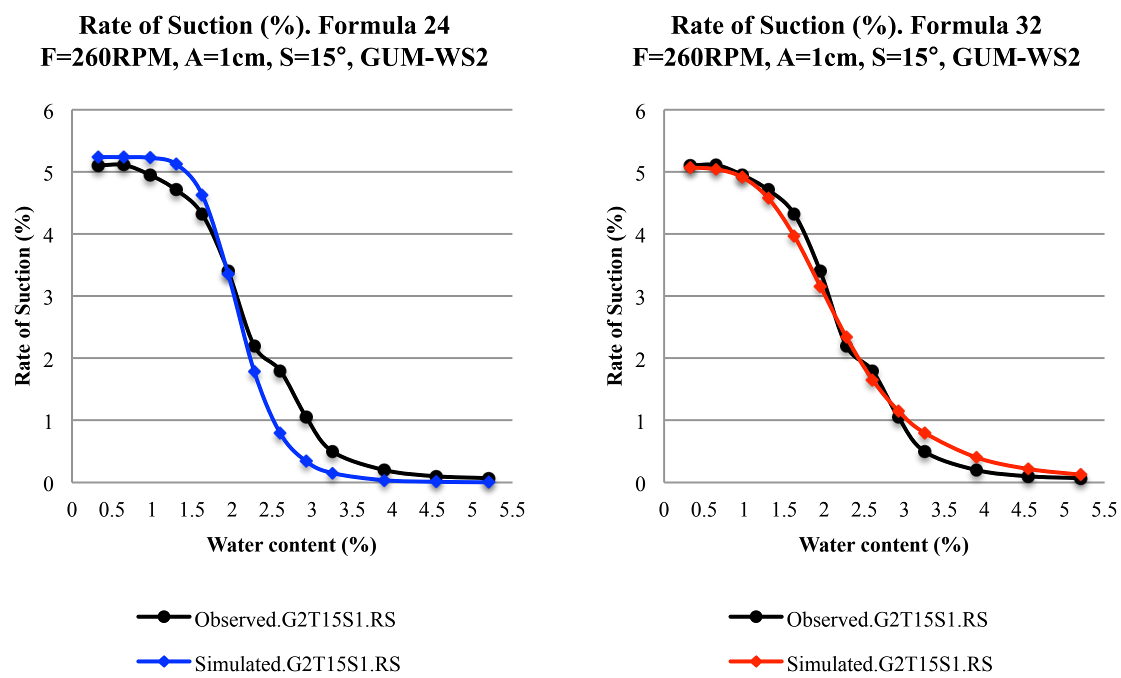

Fig. 80 Observed (G2T15S1) and simulated rate of suction (formula 24 left side and 32 right side)

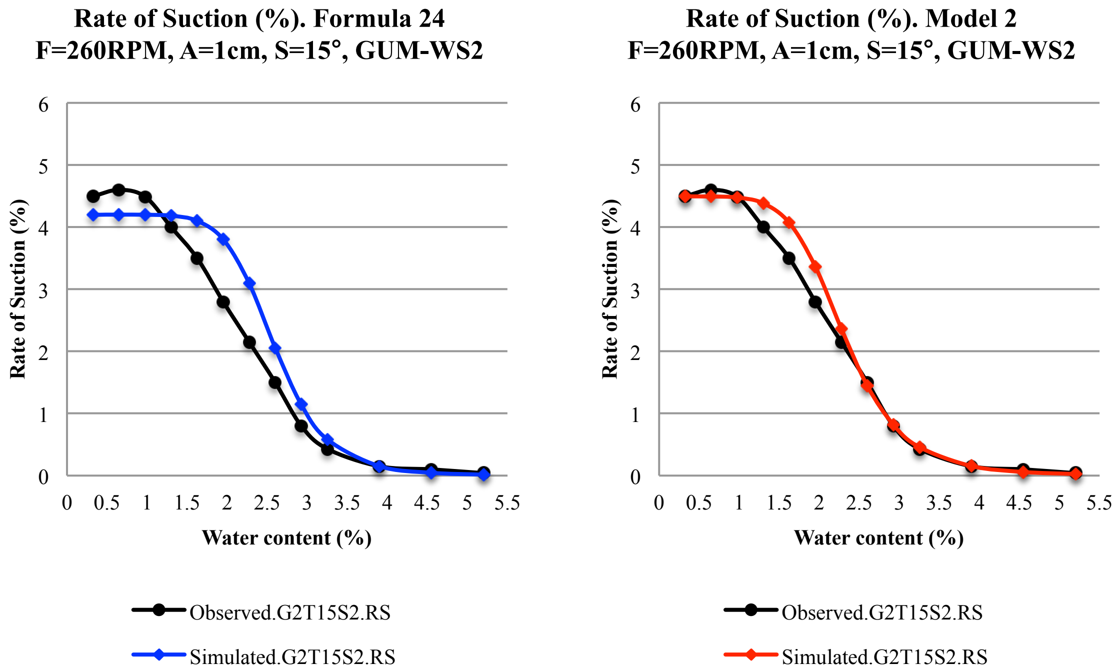

Fig. 81 Observed (G2T15S2) and simulated rate of suction (formula 24 left side and 32 right side)

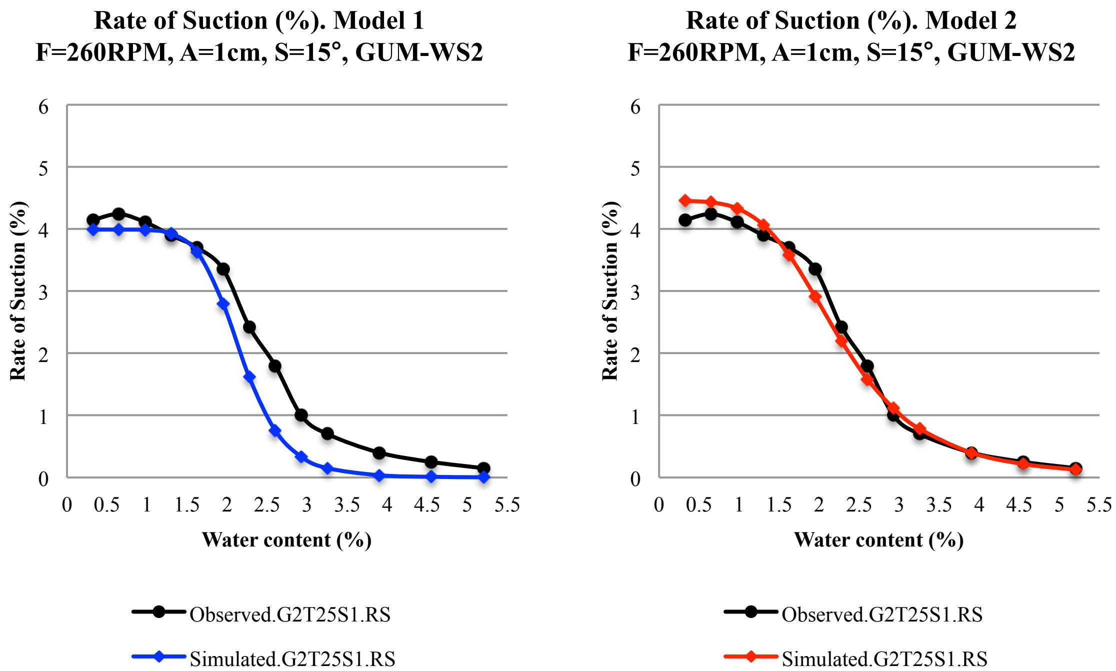

Fig. 82 Observed (G2T25S1) and simulated rate of suction (formula 24 left side and 32 right side)

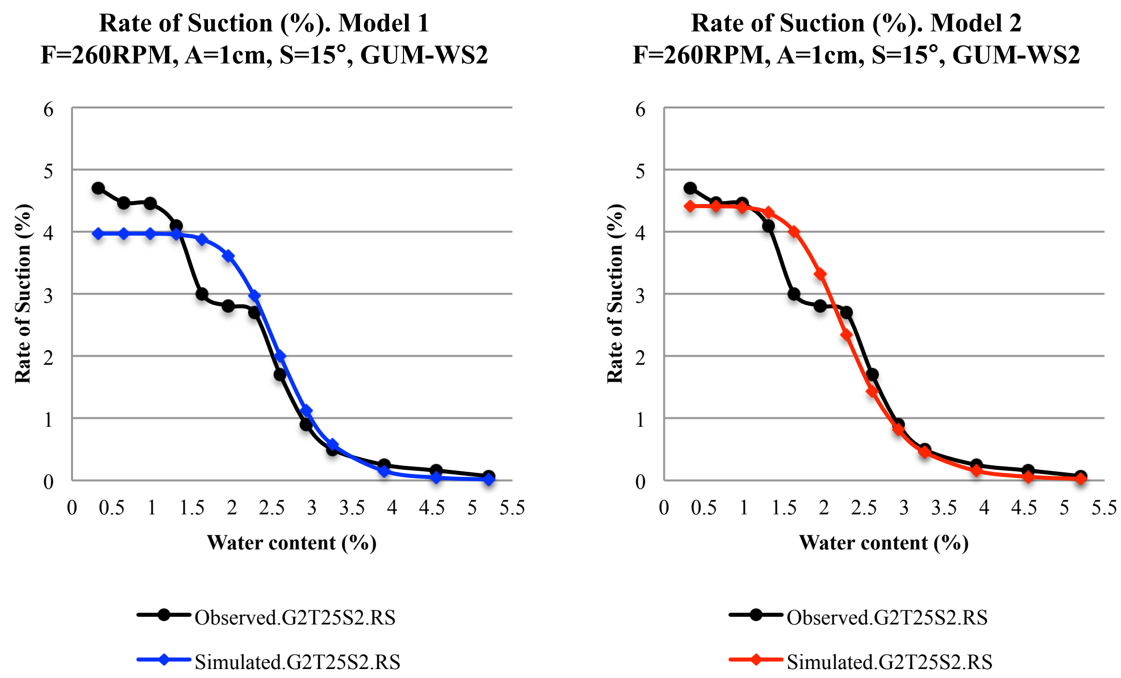

Fig. 83 Observed (G2T25S2) and simulated rate of suction (formula 24 left side and 32 right side)

After analyzing the graph information from Figure 76 to Figure 83, it is possible to conclude that simulated rate of suction from formula 32 is closer to observed rate of suction than those values obtained from formula 24 in each figure. This fact confirm that, formula 32 can be considered a better tool than formula 24, to simulate the equipment performance.

5.2 Simulation. Rate of suction.

After selecting the formula 32 as a better tool to predict the equipment performance, arise the necessity to know the rate of suction of the equipment under difference conditions. For example, it is necessary to know the equipment performance with different GUM (different specific surface area and water absorption), different soil (different clay percent and silt percent) and different temperature.

Japanese specification for crushed stone aggregate set 3.0% as a highest water absorption, in the case of the mentioned materials will be used as a component of surface or binder layers [67]. The minimum average temperature and the maximum average temperature in Sendai city are -2°C and 28°C respectively [68]. Therefore, those previous mentioned values of water absorption and temperature will be considered to simulate the equipment performance.

The simulation of equipment performance will be divided into two stages. First, it will be considered one of the used GUM-WS and soil in this research to change its characteristics step by step and then simulate the equipment performance. Second, it will be considered two imaginative contaminated GUM to simulate the equipment performance.

5.2.1 Simulation. Rate of suction changing original condition.

The first stage in the simulation of equipment performance, using the formula 32 will be carried out keeping constant and changing the original condition to process the GUM-WS1 contaminated with Soil 2 at 15°C. Table 47 shows the original and changed conditions to process the GUM-WS1 contaminated with Soil 2. The changed conditions show the lowest and highest values for each parameter that were considered to simulate the equipment performance.

Table 47 Original and changed condition to process GUM-WS1 contaminated with Soil 2

Parameters	Original condition	Changed condition
g.a (%)	1.714	0.3 – 3.0
g.sa (m^2/kg)	1.66	1.35 – 2.25
s.c (%)	11.1	10.1 – 12.1
s.s (%)	67.1	66.1 – 68.1
s.sa (%)	21.8	20.8 – 22.8
s.LL (%)	48.1	38.1 – 58.1
s.SL (%)	22.13	12.13 – 32.13
t (°C)	15	-2 – 28

Figure 84 shows the simulated rate of suction of the equipment when process the GUM-WS1 contaminated with Soil 2 under original and changed conditions, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Red, black and blue curve represent the simulated rate of suction of the equipment with g.a equal to 3.0, 1.714 (original) and 0.3 respectively.

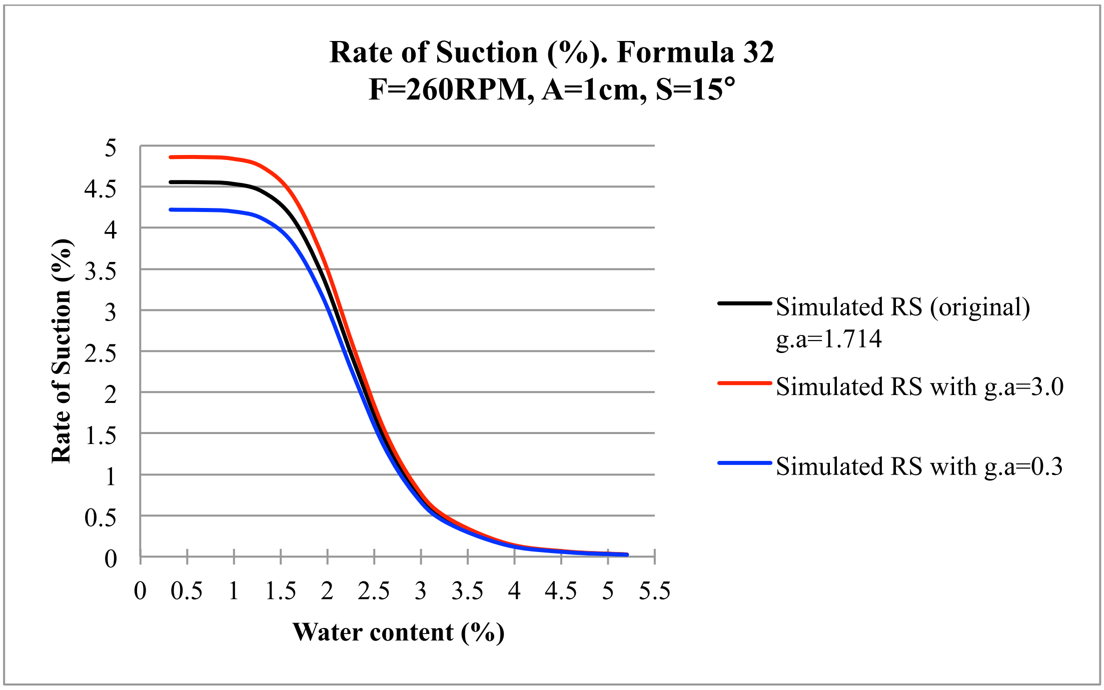

Fig. 84 Simulated rate of suction with original and changed g.a.

Analyzing the Figure 84, it is possible to conclude that, when the water absorption of GUM increases the equipment performance increases respect to the control simulated rate of suction when the water content is less than around 2.5%, because after this mentioned value, all simulated rate of suction are very similar. On the other hand, when the water absorption of GUM decreases the equipment performance decreases respect to the control simulated rate of suction when the water content is less than around 2.5%. This behaviour should be because when the mentioned parameter increases, decreases the possibility of the soil to absorb water, therefore it will be easier for the equipment reduce the soil content in GUM.

Figure 85 shows the simulated rate of suction of the equipment when process the GUM-WS1 contaminated with Soil 2 under original and changed conditions, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Red, black and blue curve represent the simulated rate of suction of the equipment with g.sa equal to 1.35, 1.66 (original) and 2.25 respectively.

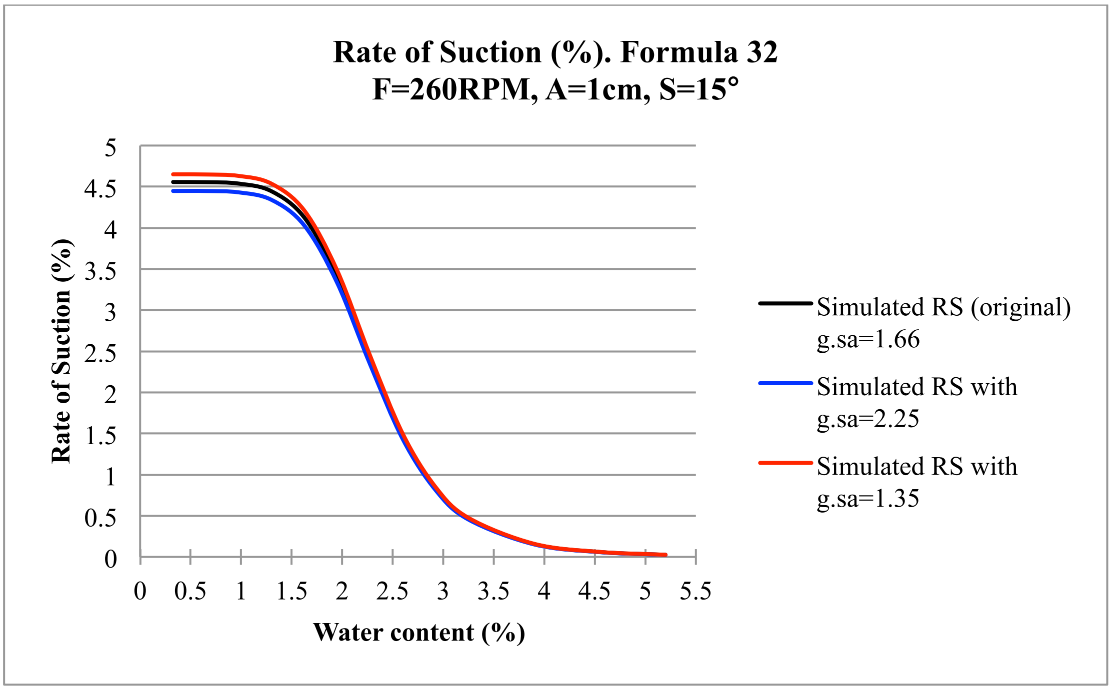

Fig. 85 Simulated rate of suction with original and changed g.sa.

After analyzing the graphs shown in Figure 85, it is possible to conclude that, when the specific surface area of GUM increases the equipment performance decreases a little bit, respect to the control simulated rate of suction when the water content is less than around 1.5%, because when water content in the material to process is higher than mentioned value, all simulated rate of suction of the equipment are very similar. On the other hand, when the specific surface area of GUM decreases the equipment performance increases a little bit respect to the control simulated rate of suction when the water content is less than around 1.5%. This behaviour should be because when the mentioned parameter increases, it will be more difficult for the swirl air flow, which is blown into the main pipe of the equipment from the tangential direction, produce a separation affect on the whole surface of the material to process.

Figure 86 shows the simulated rate of suction of the equipment when process the GUM-WS1 contaminated with Soil 2 under original and changed conditions, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Red curve represents the simulated rate of suction of the equipment with s.c, s.s and s.sa equal to 12.1, 66.1 and 21.8 respectively. Black curve represents the simulated rate of suction of the equipment with s.c, s.s and s.sa equal to 11.1, 67.1 and 21.8 respectively (original condition). Blue curve represents the simulated rate of suction of the equipment with s.c, s.s and s.sa equal to 12.1, 67.1 and 20.8 respectively.

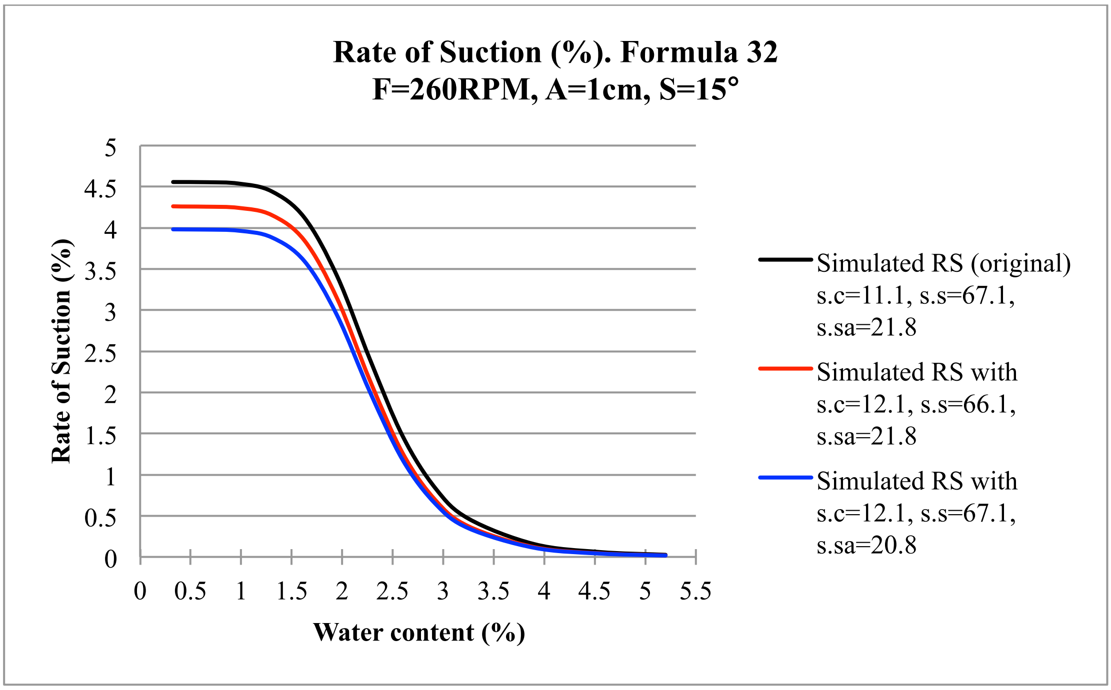

Fig. 86 Simulated rate of suction with original and increased s.c.

Figure 86 represents two specific possible cases when the clay percent increases as a component of soil. There is one case when clay percent increases and silt percent decreases keeping constant the sand percent in the soil (red curve), in this situation the equipment performance decreases respect to the control simulated rate of suction when the water content is less than around 3.5%, because when the water content is higher than the mentioned value, all simulated rate of suction of the equipment are very similar. On the other hand, there is another case where clay percent increases and sand percent decreases keeping constant silt percent in the soil (blue curve), under this condition the equipment performance decreases respect to the control simulated rate of suction of the equipment and also decreases respect to previous mentioned situation, when the water content is less than around 3.5%. This fact means, increasing clay percent and decreasing sand percent affect more the equipment performance than increasing clay percent and decreasing silt percent. This fact also prove the effect of clay percent on equipment performance.

Figure 87 shows the simulated rate of suction of the equipment when process the GUM-WS1 contaminated with Soil 2 under original and changed conditions, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Red curve represents the simulated rate of suction of the equipment with s.c, s.s and s.sa equal to 10.1, 67.1 and 22.8 respectively. Black curve represents the simulated rate of suction of the equipment with s.c, s.s and s.sa equal to 11.1, 67.1 and 21.8 respectively (original condition). Blue curve represent the simulated rate of suction of the equipment with s.c, s.s and s.sa equal to 10.1, 68.1 and 21.8 respectively.

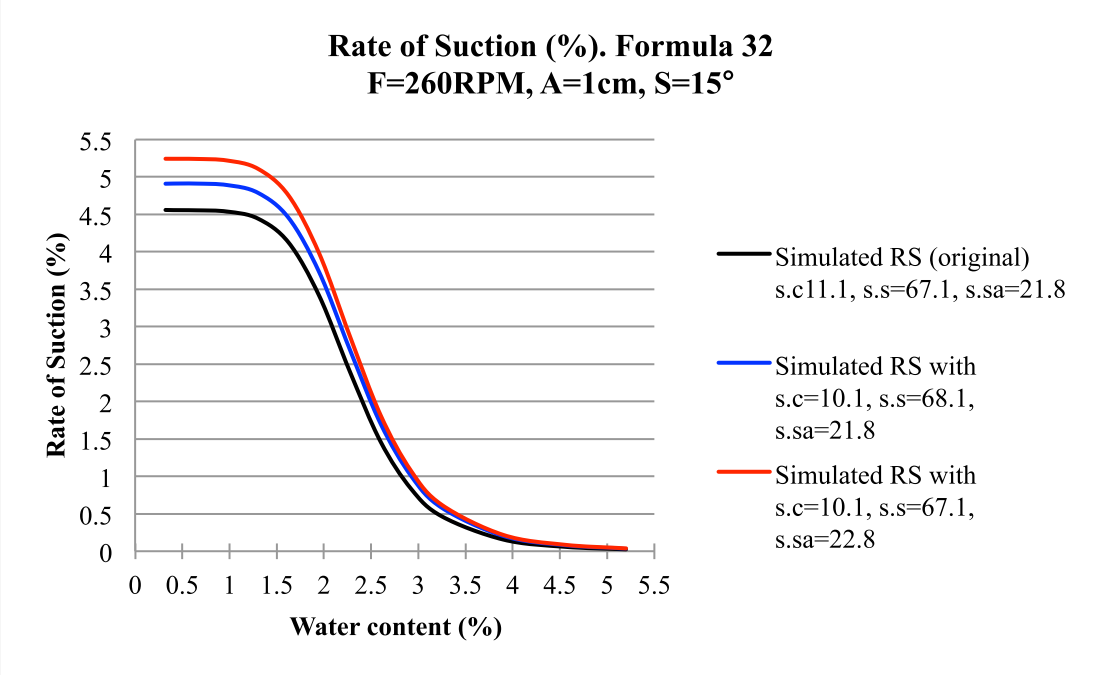

Fig. 87 Simulated rate of suction with original and decreased s.c.

Figure 87 represents two specific possible cases when the clay percent decreases as a component of soil. There is one case when clay percent decreases and silt percent increases keeping constant the sand percent in the soil (blue curve), in this situation the equipment performance increases respect to the control simulated rate of suction of the equipment when the water content is less than around 3.5%. On the other hand, there is another case where clay percent decreases and sand percent increases keeping constant silt percent in the soil (red curve), under this condition the equipment performance increases respect to the control simulated rate of suction of the equipment and also increases respect to previous mentioned situation when the water content is less than around 3.5%. This fact means, decreasing clay percent and increasing sand percent affect more the equipment performance than decreasing clay percent and increasing silt percent. This fact also prove the effect of clay percent on equipment performance.

Figure 88 shows the simulated rate of suction of the equipment when process the GUM-WS1 contaminated with Soil 2 under original and changed conditions, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Red, black and blue curve represent the simulated rate of suction of the equipment with s.LL equal to 38.1, 48.1 (original) and 58.1 respectively.

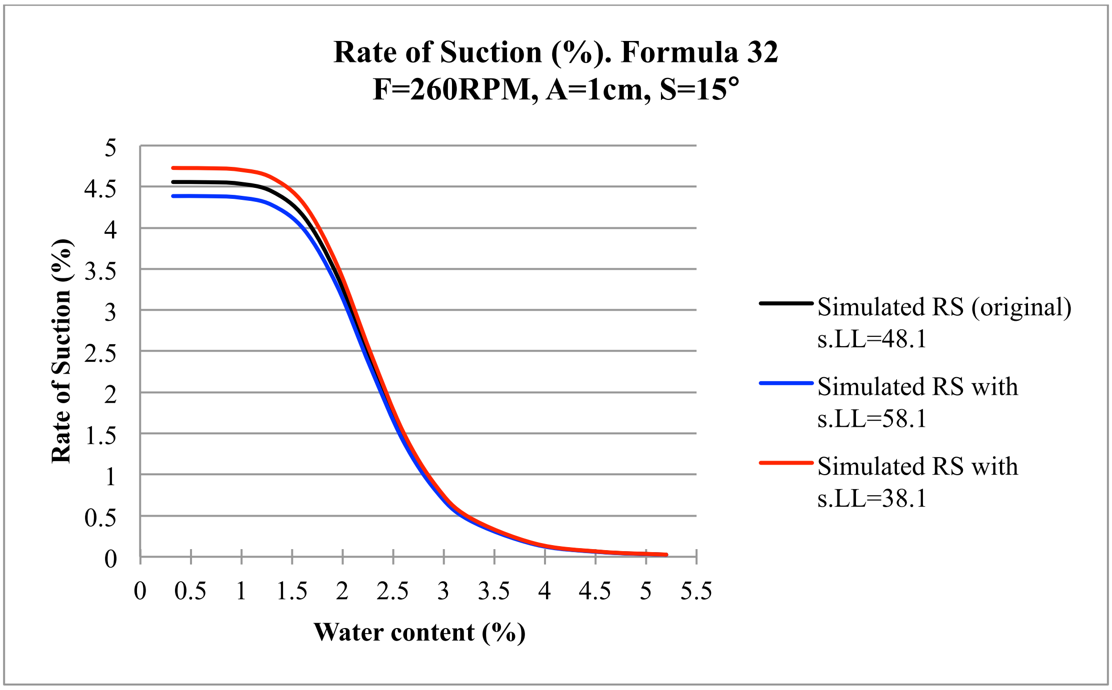

Fig. 88 Simulated rate of suction wth the original and changed s.LL.

After analyzing the graphs shown in Figure 88, it is possible to conclude that, when the liquid limit of soil increases the equipment performance decreases respect to the control simulated rate of suction of the equipment when the water content is less than 2.0%, because when the water content is higher than the mentioned value, all simulated rate of suction of the equipment are very similar. On the other hand, when the liquid limit of soil decreases the equipment performance increases respect to the control simulated rate of suction of the equipment when the water content is less than 2.0%. The water content at the liquid limit is related to surface area as closely as is clay content [69], therefore there is a functional relationship between liquid limit and external specific surface area of soils [70]. Taking into consideration previous mentioned fact, when clay percent increases in a specific soil, its liquid limit should increases, then higher percent of clay reduce the possibility to success when carry out the soil reduction content activity by the equipment.

Figure 89 shows the simulated rate of suction of the equipment when process the GUM-WS1 contaminated with Soil 2 under original and changed conditions, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Red, black and blue curve represent the simulated rate of suction of the equipment with s.SL equal to 32.13, 22.13 (original) and 12.13 respectively.

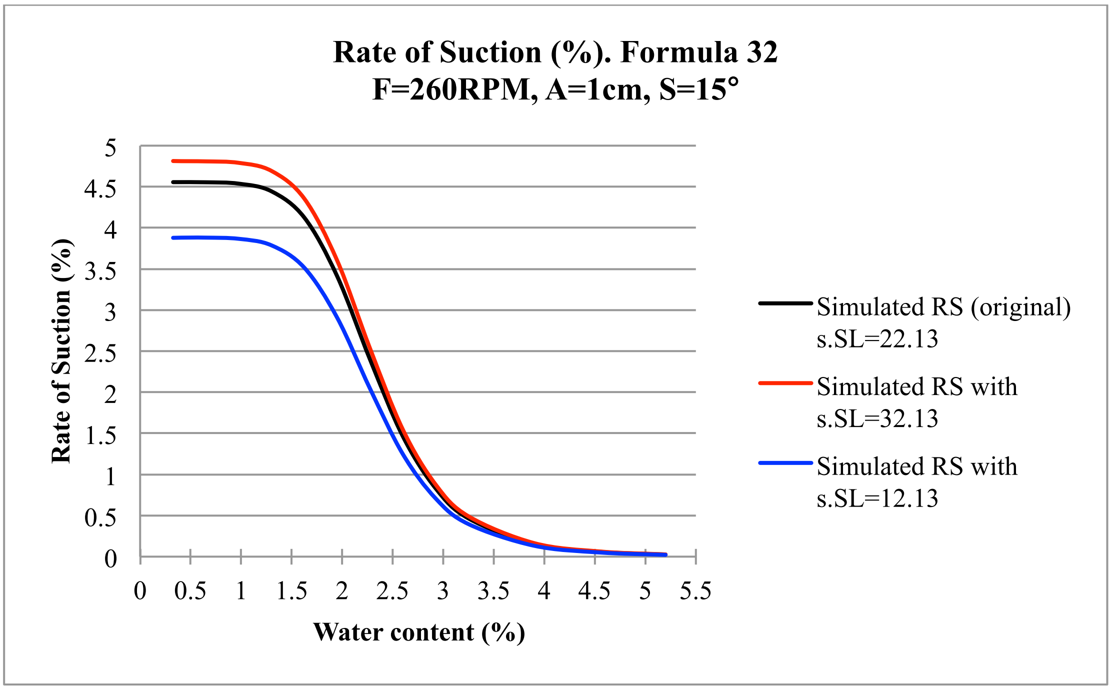

Fig. 89 Simulated rate of suction with the original and changed s.SL.

After analyzing the graphs shown in Figure 89, it is possible to conclude that, when the shrinkage limit of soil increases the equipment performance increases respect to control simulated rate of suction of the equipment when the water content is less than around 2.0%, because after this mentioned value both mentioned simulated rate of suction of the equipment are very similar. On the other hand, when the shrinkage limit of soil decreases the equipment performance decreases respect to the control simulated rate of suction of the equipment when the water content is less than around 3.0%, because when the water content is higher than this mentioned value both simulated rate of suction of the equipment are very similar.

Figure 90 shows the simulated rate of suction of the equipment when process the GUM-WS1 contaminated with Soil 2 under original and changed conditions, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Red, black and blue curve represent the simulated rate of suction of the equipment with t equal to -2, 15 (original) and 28 respectively.

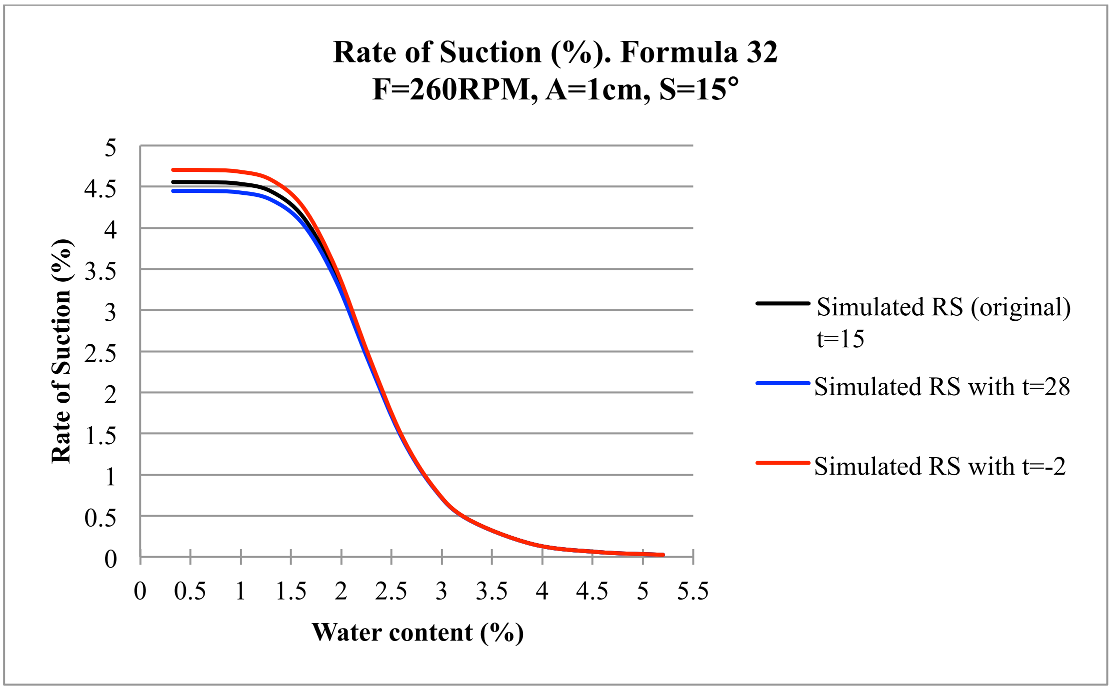

Fig. 90 Simulated rate of suction with original and changed t.

With the analysis of the graphs shown in Figure 90, it is possible to conclude that while temperature increases the equipment performance decreases a little bit respect to the control simulated rate of suction of the equipment when the water content is less than 1.5%, because when the water content is higher than this mentioned value, all simulated rate of suction of the equipment are very similar. On the other hand, while temperature decreases the equipment performance increases a little bit respect to the control simulated rate of suction of the equipment when the water content is less than 1.5%. As mentioned in "Chapter 4: Experimental Study on Soil Reduction Content in GUM Setting the Same Experimental Conditions", the temperature has a double affect on the equipment performance, taking into consideration the soil and asphalt binder properties. Soil properties are included in the obtained numerical model, but asphalt binder properties are not included. Then it is necessary in future research, obtain a numerical model taking also into consideration the asphalt binder properties.

It is possible to notice from previous simulations that, in some cases the equipment performance increases and other cases the equipment performance decreases, depending on if the considered parameter is increased or decreased. Table 48 shows values that cause the higher performance (VHP) or lower performance (VLP) of the equipment depending on the parameter.

Table 48 Values which cause increasing and decreasing of equipment performance

Parameter	VLP	Original values	VHP
g.a (%)	0.3	1.714	3.0
g.sa (m^2/kg)	2.25	1.66	1.35
s.c (%)	12.1	11.1	10.1
s.s (%)	67.1	67.1	67.1
s.sa (%)	20.8	21.8	22.8
s.LL (%)	58.1	48.1	38.1
s.SL (%)	12.13	22.13	32.13
t (°C)	28	15	-2

It is very interesting to notice from Table 48 that, silt percent in the soil is the same regardless the equipment performance. It means that even the apparatus has its higher or lower performance the silt percent in the soil, will be the same, therefore, the influence of this kind of particles on the equipment performance is very low. Figure 91 shows the simulated rate of suction of the equipment when process the GUM-WS1 contaminated with Soil 2 under original and changed conditions, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°). Red, black and blue curve represent the higher, original and lower simulated rate of suction of the equipment taking into consideration the values in Table 48.

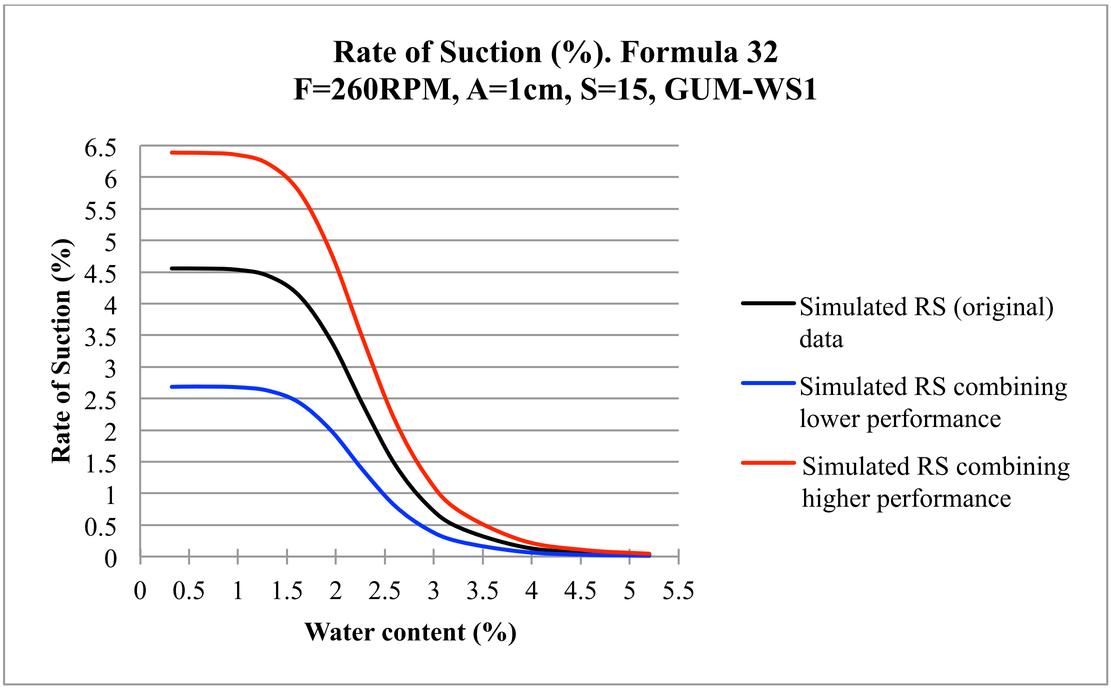

Fig. 91 Simulated rate of suction with original and changed data.

After analyzing the graphs shown in Figure 91, it is possible to conclude that, if at construction site it is necessary to process a material with the characteristics and the experimental condition listed in Table 48 (column "VHP") or (column "VLP") the equipment performance will be very different, because even it will be set in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°) the rate of suction of the equipment will be influenced by each parameter listed in Table 48. Hence, the equipment performance will increases or decreases depending on those parameter increases or decreases.

5.2.2 Simulation. Rate of suction considering two different materials.

In the second stage of simulation of the rate of suction of the equipment, using the formula 32, it will be simulated several situations at Sendai Asphalt Plant of Maeda Road Construction Co., Ltd. It will be considered that it is necessary to process in the mentioned plant, two kind of contaminated GUM, those GUM were obtained from Aobadori street (GUM-A) and Hirosedori street (GUM-H). Table 49 shows the characteristics of GUM-A and GUM-H.

Table 49 Characteristics of GUM-A and GUM-H

Parameters	GUM-A	GUM-H
g.a (%)	2.51	2.74
g.sa (m^2/kg)	1.63	1.52
s.c (%)	10.9	6.1
s.s (%)	67.5	81.2
s.sa (%)	21.6	12.7
s.LL (%)	38.6	41.9
s.SL (%)	26.2	24.1

Besides, it will be considered the same minimum and maximum average temperature in Sendai, -2°C and 28°C respectively. Figure 92 shows the simulated rate of suction of the equipment when process the GUM-A and GUM-H, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°), considering a temperature equal to -2°C (winter time). Blue and red curve represent the simulated rate of suction of the equipment when process GUM-A and GUM-H respectively.

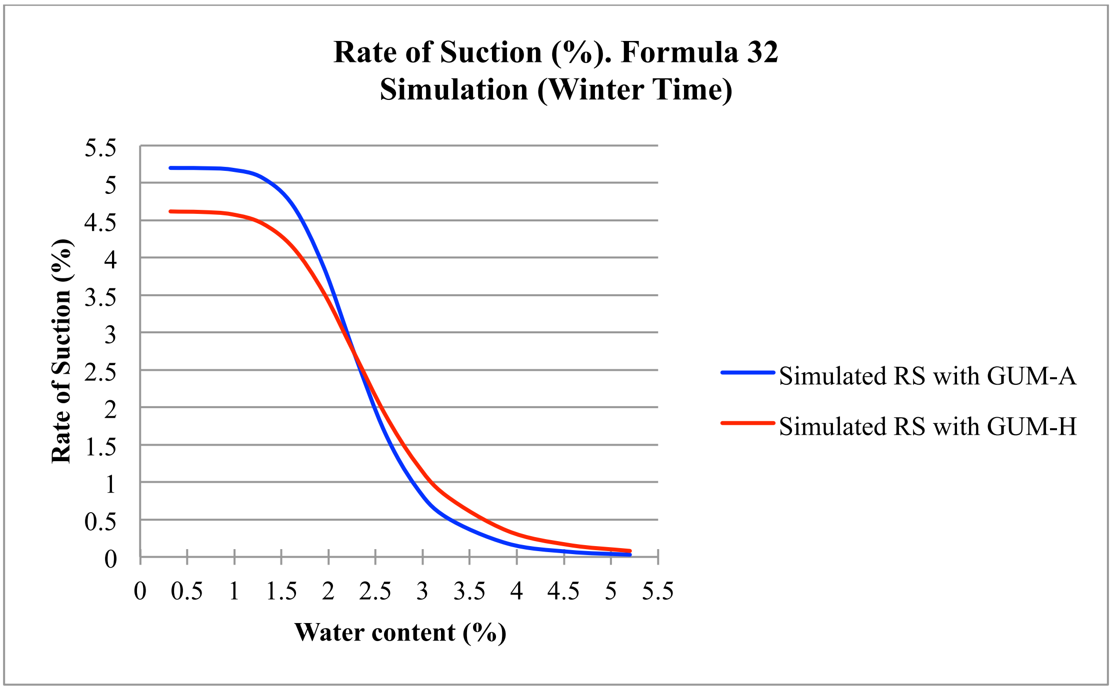

Fig. 92 Simulated rate of suction with GUM-A and GUM-H (winter time)

After analyzing the graphs from Figure 92, it is possible to conclude that, the equipment performance is higher when process the GUM-A than when process the GUM-H, while the water content in the material to process is less than around 2.3%. On the other hand, the equipment performance is higher when process the GUM-H than when process GUM-A, while the water content in the material to process is higher than around 2.3%. It is interesting to notice that, even the GUM-A is contaminated with a soil with higher clay percent, the equipment performance is higher when process this material than when process the GUM-H, while water content is less than around 2.3%. This fact is because, even the clay percent in the contaminating soil has a great influence on equipment performance, there are also other factors which can affect the rate of suction of the equipment. Besides, it is important to recommend to the Sendai Asphalt Plant of Maeda Road Construction Co., Ltd in case of rainy season or rainy day carry out the soil reduction content activity on GUM-H, but in case of dry season or dry day carry out the soil reduction content activity on GUM-A, in an attempt to obtain better performance from the proposed screenless separation equipment.

Figure 93 shows the simulated rate of suction of the equipment when process the GUM-A and GUM-H, setting in the apparatus the same frequency of vibration (260RPM), amplitude of vibration (1cm) and pipe inclination angle (15°), considering a temperature equal to 28°C (summer time). Blue and red curve represent the simulated rate of suction of the equipment when process GUM-A and GUM-H respectively.

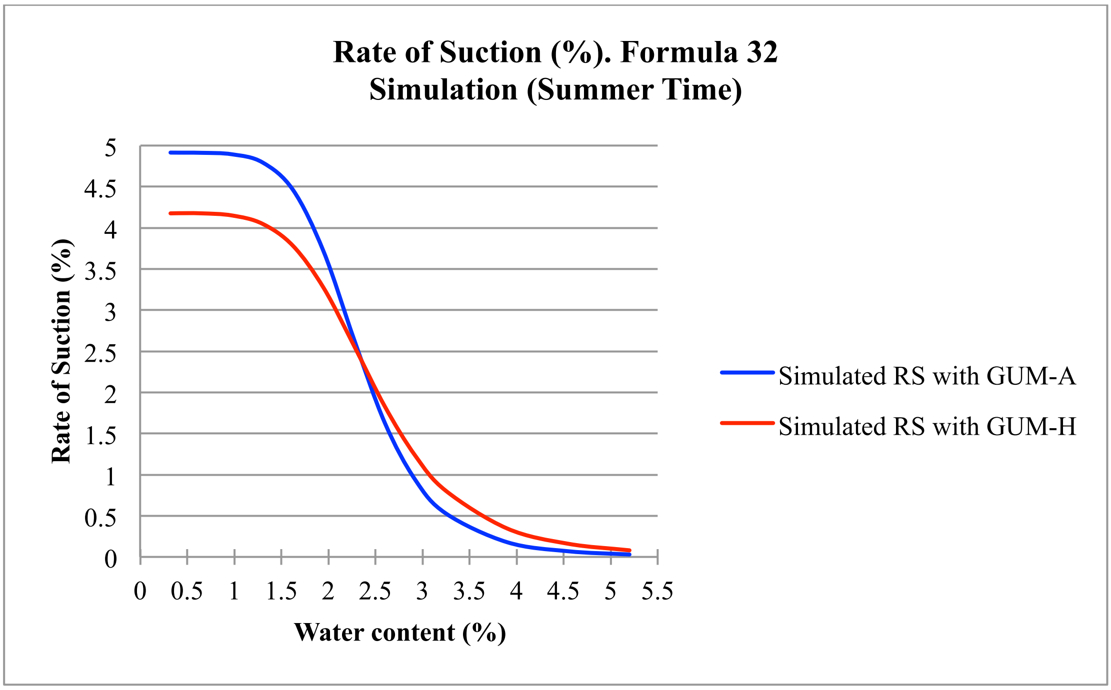

Fig. 93 Simulated rate of suction with GUM-A and GUM-H (summer time).

With the analysis of graphs from Figure 93, it is possible to conclude that, the equipment performance is higher when process the GUM-A than when process the GUM-H, while the water content in the material to process is less than around 2.3%. On the other hand, the equipment performance is higher when process the GUM-H than when process GUM-A, while the water content in the material to process is higher than around 2.3%. It is interesting to notice that, even the GUM-A is contaminated with a soil with higher clay percent, the equipment performance is higher when process this material than when process the GUM-H, while water content is less than around 2.3%. This previous behaviour of the equipment performance is the same from the winter time, this fact prove that even the temperature change, the rate of suction of the equipment will has the same tendency if the apparatus process the same materials. Besides, it is important to recommend to the Sendai Asphalt Plant of Maeda Road Construction Co., Ltd in case of rainy season or rainy day carry out the soil reduction content activity on GUM-H, but in case of dry season or dry day carry out the soil reduction content activity on GUM-A, in an attempt to obtain better performance from the proposed screenless separation equipment.

5.3 Summary of Chapter 5

As mentioned at section "**4.5 Summary of Chapter 4**", temperature has a double effect on equipment performance, because depending on the characteristics of soil attached on the surface of GUM and the characteristics of the asphalt binder contained in the GUM, the equipment performance can increases or decreases, when increasing the temperature at construction site. Therefore, it is necessary to take into consideration those 3 factors (temperature, soil and asphalt binder) in a numerical model to guarantee a good agreement between observed and simulated data.

Soil characteristics and temperature were considered as variables in the proposed numerical model in this chapter, but asphalt binder characteristics were not considered as variable. Hence, it will be necessary to include those missing characteristics, in the next proposed numerical model for guarantee a better accuracy of simulated data.

Even though, this previous fact, the following partial conclusions can be drawn, taking into consideration the results, analysis, materials and experimental conditions described in this chapter:

- The proposed numerical model (formula 32) is a suitable tool to simulate the equipment performance.
- Increasing the water absorption of GUM, sand percent and shrinkage limit of soil contained in GUM, increases the equipment performance.
- Decreasing the specific surface area of GUM, the clay percent and liquid limit of soil contained in GUM and the temperature in the laboratory, increases the equipment performance.
- Clay and silt percent in the soil have high and low effect on equipment performance respectively.
- Taking into consideration the weather condition, it can be decided which material to process at construction site, using the proposed numerical model.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS.

6.1 Conclusions. Summary of research.

This study constitute an effort to increase the usage of waste asphalt blocks as a recycled asphalt aggregate to produce new asphalt concrete. This task represents, one step forward to achieve a real sustainability in road construction. This fact is very important, because at present all kind of activity from human beings need to reduce the energy consumption as much as possible, because global warming and environmental issues.

This research was carried out with the target to achieve the defined main objectives in "**Chapter 1. Introduction".** All experiments in this study were thinking to reproduce the real conditions of construction site at the laboratory, in an attempt to be sure that experimental results in the laboratory simulate the real situation at construction site.

Even this research needs to be continued with different materials and experimental conditions; the following general conclusions can be drawn, taking into consideration all results, analysis, materials and experimental conditions described in this study:

- It was proved the usefulness of the newly proposed screenless separation equipment, because improves the previous equipment performance.
- Temperature can has a double effect on equipment performance and the final result will depend on the characteristics of the materials to process.
- It is possible to state that the success of soil reduction content activity depend on four groups of factors: factors related with the equipment design, factors related with the characteristics of the GUM, factors related with the characteristics of soil contained in GUM and factors related with the weather conditions.
- Decreasing the pipe inclination angle of the equipment, increases the equipment performance (rate of suction), regardless the frequency.
- Recovery mainly depend on the frequency of vibration and pipe inclination angle.
- Attached materials on the inner surface of the pipe decreases when increasing the frequency of vibration.
- Changing only the soil or GUM and temperature at the same time, caused highest effect on rate of suction.
- Changing only the soil, caused highest effect of equipment recovery.
- Changing GUM and soil at the same time, caused highest effect on attached materials.

- Increasing the water absorption of GUM, sand percent and shrinkage limit of soil contained in GUM, increases the equipment performance.
- Decreasing the specific surface area of GUM, the clay percent and liquid limit of soil contained in GUM and the temperature in the laboratory, increases the equipment performance.
- Clay and silt percent in the soil have high and low effect on equipment performance respectively.
- The proposed numerical model (formula 32) is a suitable tool to simulate the equipment performance.
- The obtained numerical model can be used as a tool for decision-making at construction site.
- Movement properties of GUM with 1% of water content are different from these properties when GUM contains 3 and 5% of water content.
- Movement properties of GUM with 3% and 5% of water content are similar.

6.2 Recommendations

As mentioned before, it is still necessary to continue with this study, because there are several conditions to take into consideration to improve the knowledge about the soil reduction content activity in GUM. It is believed that considering the following aspects will help for decision-making at construction site and the success of soil reduction content activity in GUM in the near future:

- To carry out experiments with others GUM, soil and temperature at the laboratory.
- To carry out experiments taking into consideration the characteristics of asphalt binder.
- To obtain a numerical model to predict the equipment performance, taking into consideration the characteristics of asphalt binder.
- To carry out a design of recycled asphalt mixtures using the processed GUM by the screenless equipment in the laboratory.
- To carry out experiments at construction site using a full-scale equipment, taking into consideration the whole experience obtained from the experiments in the laboratory.
- To carry out a design of recycled asphalt mixtures, at construction site, using the processed GUM by the full-scale equipment.

- To produce the designed recycled asphalt mixture and use it to build a test section, to verify the performance of the mentioned mixture on service.

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